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VOLUME 9, NO. 4 APRIL, 1956

CONTENTS

PAGE

EDWARD L. P. MERCY: The accuracy and precision of "rapid methods" of silicate analysis 161

K. I. MAYNE: Terrestrial helium 174

LESTER WINSBERG: The production of chlorine-39 in the lower atmosphere by cosmic radiation 183

MARJORIE HOOKER: Data of rock analyses—II. Bibliography and index of rock analyses in the African periodical and serial literature 190

Letter to the Editors:

V. P. SOKOLOFF, A. SEROUSSI, and Y. ISRAEL: Trace-metal anomalies in sedimentary rock over petroleum-bearing horizons 214

Book Reviews:

"A New Periodic Table of the Elements" by S. I. TOMKEIEFF (reviewed by L. H. AHRENS) 215

"Chikyu-Kagaku (Geochemistry)" by YASUO MIYAKE (reviewed by P. K. KURODA) . . . 215

News and Notes 216

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The accuracy and precision of "rapid methods" of silicate analysis

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(*Received* 29 *September* 1955)

Abstract—The "rapid methods" of silicate analysis devised by SHAPIRO and BRANNOCK (1952) are criticized. One major modification (the method for total Fe) and one minor modification (the titration of Ca solutions) are proposed. The accuracy and precision of the methods are stated and shown to be adequate for the analysis of silicate rocks in the diorite-granite range. Suggestions are given for further research.

1. INTRODUCTION

IN recent years some attention has been given to the problem of evaluating the accuracy and precision of conventional chemical methods for the analysis of silicate rocks. Co-operative investigations of the analysis of a granite and a diabase (FAIRBAIRN *et al.*, 1951; SCHLECHT, 1951; FAIRBAIRN, 1953) showed that inter-laboratory precision was much less than had been supposed. At much the same time work had been proceeding on a system of rapid colorimetric methods for the determination of the major and minor constituents of silicate rocks, and this was published in America (SHAPIRO and BRANNOCK, 1952*). Other systems for the rapid analysis of silicate materials have been proposed (see, for example, HEDIN, 1947; COREY and JACKSON, 1953; BANNERJEE and COLLISS, 1955), but will not be discussed here, since they are considered to be generally inferior to the procedures adopted by SHAPIRO and BRANNOCK.

This paper is (1) a criticism, based on the experience gained by performing some two-hundred analyses of granitic rocks, of the system of SHAPIRO and BRANNOCK; and (2) a presentation of data which show the accuracy and precision that can be obtained by one analyst working under routine conditions.

2. METHODS OF ANALYSIS

In the analyses quoted in this paper all photometric measurements were made with a Hilger "Uvispek" spectrophotometer.

SiO_2 and Al_2O_3 are determined on a 0·1-g sample after fusion with NaOH, SiO_2 by a molybdenum blue method (BUNTING, 1944), and Al_2O_3 by its complex with ferron (DAVENPORT, 1949). Despite the high dilution factor (200,000), the method for SiO_2 gives exceedingly good results when applied to dioritic and granitic rocks. The ferron process for Al_2O_3 is mediocre. It suffers from the disadvantage of interference from Fe and Ti and, in practice, tends to give aberrant results in about 5 per cent of cases. Such aberrant results have to be discarded and the

* *Note added in proof, January*, 1956, *E. L. P. M.*—The original publication by SHAPIRO, L., and BRANNOCK, W. W. (American Geol. Surv. Circular 165), has now been revised by these authors and published as Am. Geol. Surv. Bull. 1036-C. New methods for Al, total Fe, and Ti are proposed and a new procedure given for the titration of Ca and Mg.

analysis repeated. Attempts to apply to silicates other methods for the determination of Al_2O_3, e.g., the aluminon process, were unsuccessful. Recent work with versene (FLASCHKA *et al.*, 1953) may lead to a more accurate determination of Al_2O_3 in silicates.

A 1·0-g sample, after treatment with H_2SO_4 and HF, is used for the determination of CaO, MgO, Na_2O, K_2O, total Fe as Fe_2O_3, TiO_2, MnO, and P_2O_5.

After removal of Al, Fe, and Ti, CaO and MgO are determined by titration with versene (BETZ and NOLL, 1950) and good results can be obtained, provided the modifications of CHENG and BRAY (1951) are adopted. Although the titration end-point is somewhat difficult to discern, with practice the determination of CaO can be made with a high degree of precision. The titration may be avoided by using the photometric determination of the end-point devised by CHALMERS (1954). When the concentration of MgO greatly exceeds that of CaO (about ten times, or more) good results for CaO cannot be obtained, since the precipitated $Mg(OH)_2$ adsorbs the dye (murexide) used in the titration, and interferes with the end-point. Since the determination of MgO is not direct, being dependent upon a prior determination of CaO (which is bad analytical practice), efforts have been made to apply the Titan Yellow and 8-quinolinol processes, but these were unsuccessful. The former process suffers from interference by NH_4^+ and Ca^{++} and is not precise, while the latter process requires far too much chemical manipulation, which is contrary to the idea of rapid methods.

Na_2O and K_2O are determined by means of flame photometry with satisfactory results. The process used in obtaining the data given in this paper is that described by SHAPIRO and BRANNOCK (1952), using Li as the internal standard, but the technique and the apparatus are not the same. In this work the Lundegardh technique (MITCHELL, 1948) was used (air-pressure 30 lb/sq in.; acetylene pressure of 20 cm of water) and the per cent transmission measured by the "Uvispek" spectrophotometer. The flame emission technique requires careful control of a number of variables; in particular, since the lines due to Li, Na, and K are narrow, the wavelength setting requires careful control. Simplified instruments are now available which not only reduce the number of variables but also the time required for measurement.

Total Fe is determined by SHAPIRO and BRANNOCK as the yellow ferric chloride complex (PINSL, 1944). This method cannot be recommended. Amongst other disadvantages, the intensity of the colour is seriously affected by the ambient temperature. In this work it has been replaced by the ferrous-iron complex with thioglycollic acid (MILNER and GROOM, 1951), which gives very good results.

TiO_2, MnO, and P_2O_5 are determined photometrically by adaptations of well-known processes—TiO_2 as "pertitanic acid," MnO as permanganic acid, and P_2O_5 as the molybdivanadophosphoric acid complex.

Ferrous iron is determined by the conventional method (GROVES, 1937) using potassium dichromate as the titrant and diphenylamine sulphonic acid as internal indicator.

H_2O^+ is determined by ignition in a tube furnace at 950°C and absorption of the expelled water in $CaCl_2$ drying-tubes.

In this work the analyses were done on 60-mesh material dried at 110°C.

3. The Assessment of Accuracy and Precision

The absolute error of a determination is the difference between the observed or measured value and the true or most probable value of the quantity measured. The absolute error is a measure of the accuracy of the measurement. The accuracy of a determination may therefore be defined as the concordance between it and the true or most probable value. To measure the accuracy of the rapid methods, six dilutions of W1 in G1 (the American diabase and granite—Fairbairn *et al.*, 1951) were prepared, and these, together with W1 and G1, were analysed by means of single determinations. The American standards were obtained through the courtesy of Dr. Michael Fleischer, Geological Survey, Washington, D.C.

The most probable values for the standards W1 and G1 were taken to be the consensus means given in *U.S. Geol. Survey Bull.* 980, Tables 19 and 20, p. 41 (Fairbairn *et al.*, 1951), modified to include the revised figures for SiO_2 and Al_2O_3 (Fairbairn, 1953). The analyses of the dilutions 1–6 were calculated from these consensus means. The results are given in Table 1.

Precision may be defined as the concordance of a series of measurements of the same quantity. In order to measure the precision of the rapid methods, two rocks, one granitic and one dioritic, were each analysed six times. The results are given in Tables 3 and 4. M149 (G1-type, Rosses) is a medium-grained biotite-granite, and has been fully described by Pitcher (1953a). T13 is a coarse-grained dioritic phase of the Older Granodiorite of Thorr District, Co. Donegal, described by Pitcher (1953b).

To keep a check on precision during the course of the analysis of some 170 granitic rocks from Co. Donegal, Ireland, every tenth sample was analysed in duplicate. The results are given in Tables 7 and 8.

Before discussing the accuracy and precision of the rapid methods, the conditions under which the data of Tables 1, 3, 4, 7, and 8 were obtained should be stated. Between February 1954 and April 1955 about 170 granitic rocks, chosen to illustrate the geochemistry of part of the Donegal Granite, were collected, sampled, crushed, and analysed for their major and minor constituents. The analyses were done in batches of twenty (SiO_2 and Al_2O_3), two (H_2O^+), and six (all other oxides). The eight analyses of Table 1 were obtained individually at eight separate times, each sample constituting part of one batch. The precision analyses of M149 and T13 (Tables 3 and 4) each constituted such a batch. The first and second analyses of Tables 7 and 8 were done in separate batches, the individual samples being spread through the whole period of analysis. In all, some two-hundred analyses were made between September 1954 and April 1955. Since late October 1954 a research assistant has helped with the work.

Thus, the data presented in this paper have been collected under routine conditions of work, and must be judged accordingly.

4. The Accuracy of the Rapid Methods

The data given in Table 1 show the accuracy of the rapid methods when judged by the most probable values for the standards W1 and G1. In the discussion which follows, any bias in the consensus mean figures for W1 and G1 is taken into account.

Table 1. The accuracy of the rapid methods determined by single analyses of W1 and G1

	W1			1			2			3			4			5			6			G1		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
SiO_2	52·9	53·4	0·9	55·9	55·3	1·1	58·9	59·2	0·5	61·9	62·5	1·0	64·9	64·4	0·8	68·0	68·0	0	71·0	71·0	0	73·0	72·5	0·7
TiO_2	1·1	1·1	0	0·95	0·98	3·2	0·83	0·85	2·4	0·70	0·72	2·8	0·58	0·60	3·4	0·46	0·49	6·5	0·33	0·35	6·1	0·25	0·26	4·0
Al_2O_3	14·8	14·7	0·7	14·6	14·4	1·4	14·5	14·1	2·8	14·3	13·8	3·5	14·2	14·3	0·7	14·0	14·4	2·8	13·9	13·3	4·3	13·8	14·0	1·4
Fe_2O_3	1·3	1·3	0	1·2	1·3	8·3	1·2	1·3	8·3	1·1	1·2	9·1	1·0	1·1	10	0·91	0·98	7·7	0·84	0·81	3·6	0·79	0·76	3·8
FeO	8·8	8·8	0	7·6	7·6	0	6·4	6·3	1·6	5·3	5·1	3·8	4·1	4·0	2·4	2·9	2·9	0	1·8	1·7	5·6	1·0	0·94	6·0
MnO	0·18	0·14	22	0·16	0·14	12·5	0·14	0·10	28	0·11	0·12	9·1	0·09	0·07	22	0·07	0·06	14	0·04	0·03	25	0·03	0·02	33
MgO	6·7	6·7	0	5·7	5·9	3·5	4·8	4·4	8·3	3·9	4·0	2·6	2·9	2·9	0	2·0	2·0	0	1·1	1·1	0	0·45	0·46	2·2
CaO	11·0	10·8	1·8	9·5	9·3	2·1	8·1	8·1	0	6·6	6·8	3·0	5·2	5·1	1·9	3·8	3·6	5·3	2·3	2·2	4·3	1·4	1·5	7·1
Na_2O	2·1	2·4	14	2·3	2·6	13	2·5	2·7	8·0	2·7	3·1	15	2·8	3·2	14	3·0	3·2	6·7	3·2	3·4	6·2	3·4	3·8	12
K_2O	0·65	0·70	7·7	1·4	1·5	7·1	2·1	2·2	4·8	2·8	2·9	3·6	3·5	3·7	5·7	4·2	4·1	2·4	5·0	4·8	4·0	5·4	5·4	0
P_2O_5	0·14	0·15	7·1	0·13	0·12	7·7	0·13	0·13	0	0·12	0·12	0	0·12	0·10	17	0·11	0·10	9·1	0·10	0·08	20	0·10	0·08	20
H_2O^+	0·55	0·6	0	0·52	0·5	0	0·50	0·5	0	0·47	0·4	20	0·44	0·6	50	0·42	0·5	25	0·39	0·5	25	0·37	0·4	0
Fe°	11·1	11·1	0	9·7	9·7	0	8·4	8·3	1·2	7·0	6·9	1·4	5·6	5·5	1·8	4·2	4·2	0	2·8	2·7	3·6	1·9	1·8	5·3
Total	100·2	100·8	0·6	100·0	99·6	0·4	100·1	99·9	0·2	100·0	100·8	0·8	99·8	100·1	0·3	99·9	100·3	0·4	100·0	99·3	0·7	100·0	100·1	0·1

Columns *a* are the calculated figures for W1 and G1 and six dilutions of W1 in G1. The figures for W1 in G1 are the consensus means given in *U.S. Geol. Survey Bull.* 980 Tables 19 and 20, p. 41 (FAIRBAIRN *et al.*, 1951), modified to include the revised figures for SiO_2 and Al_2O_3 (FAIRBAIRN, 1953).
Columns *b* are the results of single analyses of W1, G1, and the mixtures 1–6.
Columns *c* are the per cent differences between columns *a* and *b*.
Fe° denotes total Fe expressed as Fe_2O_3.

The data also give an indication of the error of a single analysis, the evaluation of which was a problem considered by FAIRBAIRN (1953).

SiO_2. Within the range 52–73 per cent SiO_2 the method is highly accurate, since single determinations show an average error of only 0·6 per cent of the amount present. The maximum error is +1·0 per cent and −1·1 per cent of the amount present.

TiO_2. Within the range 0·25–1·1 per cent TiO_2 there is a constant positive error which amounts to about 3 per cent of the amount present at concentrations $>0{\cdot}5$ per cent TiO_2 and to about 6 per cent at concentrations $<0{\cdot}5$ per cent TiO_2. In view of the fact that TiO_2 is invariably determined by the colour due to pertitanic acid, this positive error is probably due to an effect of the particular measuring instrument used. However, the error is relatively small and the method may be described as accurate.

Al_2O_3. At the concentration level of 14–15 per cent Al_2O_3, the Ferron process appears to be moderately accurate, since the average error is ± 2 per cent of the amount present and the maximum positive and negative deviations are +2·8 per cent and −4·3 per cent respectively. Since Al is an important constituent of most silicates and is present generally in amounts >10 per cent Al_2O_3, a more accurate method is desirable; its determination should ideally be accurate to within ± 1 per cent of the amount present.

Total Fe. Within the range 2–11 per cent Fe expressed as Fe_2O_3, the thioglycollic-acid process gives accurate results, the average deviation being −1·7 per cent of the amount present. At concentrations >3 per cent Fe_2O_3, the average deviation is only −0·7 per cent of the amount present. It should be noted that the errors are always negative, and this may be a function of the method. However, this is not necessarily true since the histograms of *Bull.* 980 show a wide dispersion for total Fe, this being due, in part, to the six different methods for Fe used by the co-operating analysts.

FeO. The conventional procedure for FeO gives accurate results within the range 1–9 per cent FeO, the average deviation being −2·4 per cent of the amount present, which decreases to −1·3 per cent at concentrations >2 per cent FeO. The consistent negative error may be due to the operator, but the histogram for FeO in *Bull.* 980 shows an extraordinary wide variation for the diabase W1, so that the consensus mean figure for W1 may be biased.

Fe_2O_3. The error of the figures for Fe_2O_3 (which are of course calculated from the figures for total Fe and FeO) amounts to ± 6 per cent of the amount present within the range 0·8–1·3 per cent Fe_2O_3. There is a tendency for the errors to be positive. Reference to Table 20 of *Bull.* 980 shows that the arithmetic and consensus means for G1 and for W1 differ by approximately 10 per cent and 20 per cent respectively. Taking this into consideration, it may be said that Fe_2O_3 can be calculated with reasonable accuracy.

MnO. Within the range 0·03–0·18 per cent MnO the accuracy is poor, the average error being about 20 per cent of the amount present. This error is negative except in the case of dilution 3. The histograms of *Bull.* 980 also show that MnO cannot be determined, at low concentrations, with any approach to accuracy. The matter requires investigation.

MgO, CaO. The determination of MgO, being indirect, might be expected to show a poor degree of accuracy. The average error of ± 2 per cent of the amount present within the range 0·4–7 per cent MgO seems very reasonable. The large negative error ($-8{\cdot}3$ per cent) of dilution 2 probably indicates incomplete removal of Al_2O_3 prior to titration. For CaO the error of ± 3 per cent of the amount present within the range 1·4–11 per cent CaO is also considered to be very reasonable, especially when the difficult nature of the titration end-point is taken into account. The method of analysis for MgO and CaO is not easy and requires considerable attention to detail. However, a better chemical method, which would also be as rapid, probably does not exist.

Na_2O, K_2O. It is not very satisfactory to compare flame photometric procedures with the conventional methods for Na_2O and K_2O, since the latter processes are subject to negative errors due to incomplete extraction of the alkali elements and relatively high solubility of the compounds prepared for weighing. The figures given in Table 1 show that flame photometric determinations of Na_2O are on the average 11 per cent too high, and judged by this standard the method is inaccurate. However, taking the figures of 2·4 per cent Na_2O for W1 and 3·8 per cent for G1 (instead of the consensus mean figures of 2·1 and 3·4) as representing the most probable values, the six dilutions give the following calculated and observed figures:

1		2		3		4		5		6	
2·6	2·6;	2·8	2·7;	3·0	3·1;	3·2	3·2;	3·4	3·4;	3·7	3·4

From these figures the average error within the range 2·6–3·7 per cent Na_2O is seen to be $\pm 3{\cdot}5$ per cent of the amount present, which is reasonably accurate.

Flame photometric determinations of K_2O correspond more nearly to the calculated figures, although there is an indication of a small positive error in five out of the eight sets of figures. The average deviation is $\pm 4{\cdot}4$ per cent of the amount present within the range 0·65–5·4 per cent K_2O, which is considered to be moderately accurate.

Table 2. Results with different methods of determining Na_2O.

	1	2	3
G1	3·4	3·6	3·8
W1	2·1	2·3	2·4

Column 1—The consensus mean figures, thirty-four analysts, seven methods.
Column 2—The arithmetic mean of eight determinations by flame photometer (1 analyst) taken from Table 16, *Bull.* 980.
Column 3—Single determinations by flame photometer.

It should be noted that other analysts obtain "high" figures for Na_2O when using the flame photometer. Thus Table 16 of *Bull.* 980 gives the results of precision analyses for Na_2O in G1 and W1. These figures are reproduced in Table 2 together with the appropriate figures from Table 1.

P_2O_5. Within the range 0·1–0·14 per cent P_2O_5 the method is accurate to ± 10 per cent of the amount present, which at this small concentration is quite

reasonable. The co-operating analysts all used gravimetric processes for determining P_2O_5.

H_2O^+. Within the range 0·37–0·55 per cent H_2O^+ the accuracy is about ±15 per cent of the amount present, which is poor. Since the precision of the method is also poor (see below), the observed figures are only given to one decimal place.

Totals. The average deviation is ±0·4 per cent of the amount present, which is very satisfactory indeed, and also shows that there are no strongly biased errors in any of the methods.

On the assumption that the following arbitrary limits of error could reasonably be expected from a single analysis of silicate rock by the rapid methods :—

Per cent constituent	Error, per cent of amount present
15–75	±1
5–15	±2
1–5	±5
0·1–1	±10

then the methods may be classified as (1) accurate—those for SiO_2, TiO_2, total Fe, FeO, MgO, CaO, Na_2O, K_2O, and P_2O_5; (2) moderately accurate—those for Al_2O_3, Fe_2O_3, and MnO; (3) inaccurate—that for H_2O^+.

5. The Precision of the Rapid Methods

In Tables 3 and 4 are given the results of precision analyses of a granite and a diorite, together with the usual statistical data. From a study of these tables it can be seen that for single observations made under routine conditions, the determinations of SiO_2 (av. C = 0·42 per cent), total Fe (av. C = 2·1 per cent), FeO (av. C = 2·1 per cent), MgO (av. C = 2·2 per cent), CaO (av. C = 0·88 per cent), Na_2O (av. C = 1·8 per cent), K_2O (av. C = 3·0 per cent), and P_2O_5 (av. C = 2·6 per cent), all are precise; whereas the determinations of TiO_2 (av. C = 6·9 per cent), Al_2O_3 (av. C = 3·0 per cent), Fe_2O_3 (av. C = 6·9 per cent), and MnO (av. C = 7·4 per cent), are moderately precise; and the determination of H_2O^+ (av. C = 14·4 per cent) lacks precision.

Combining these results with those obtained from a consideration of Table 1, it may be said that single determinations by rapid methods of SiO_2, total Fe, FeO, MgO, CaO, Na_2O, K_2O, and P_2O_5 are all precise and accurate; single determinations of TiO_2 are accurate but only moderately precise; single determinations of Al_2O_3 and Fe_2O_3 show only moderate accuracy and precision; single determinations of MnO show poor accuracy but moderate precision; and single determinations of H_2O^+ show poor accuracy and are imprecise.

The columns marked *E* in Tables 3 and 4 show the relative error of the mean in terms of per cent of the amount present. Under the stated conditions—six analyses—the mean for all determinations, except that of H_2O^+, has a high degree of precision. By making the appropriate calculations it can be shown that, within the range of concentrations covered by Tables 3 and 4, duplicate analyses would give values of *E* of less than 2 per cent for SiO_2, FeO, MgO, CaO, Na_2O, K_2O, and

Table 3. Six analyses of M149-G1 type granite. The Rosses, Co. Donegal, Ireland

	1	2	3	4	5	6	$\bar{x}$	S	$S\bar{x}$	C	E
SiO_2	72·9	73·6	73·3	73·8	73·1	73·5	73·4	0·33	0·14	0·46	0·19
TiO_2	0·20	0·22	0·21	0·19	0·22	0·20	0·21	0·01	0·005	6·0	2·5
Al_2O_3	14·3	14·4	14·3	13·3	14·7	13·9	14·2	0·49	0·20	3·5	1·4
Fe_2O_3	0·57	0·57	0·52	0·54	0·59	0·49	0·55	0·04	0·02	6·8	2·8
FeO	0·93	0·93	0·97	0·96	0·91	0·91	0·94	0·03	0·01	2·7	1·1
MnO	0·05	0·04	0·04	0·04	0·04	0·04	0·04	0·004	0·002	11·2	4·6
MgO	0·82	0·80	0·80	0·79	0·81	0·79	0·80	0·01	0·005	1·5	0·60
CaO	0·95	0·93	0·93	0·93	0·93	0·94	0·94	0·009	0·004	0·95	0·39
Na_2O	4·1	4·0	4·2	4·1	4·2	4·1	4·1	0·08	0·03	1·9	0·77
K_2O	4·2	4·3	4·0	4·1	4·2	4·1	4·2	0·12	0·05	2·8	1·2
P_2O_5	0·09	0·09	0·08	0·08	0·10	0·09	0·09	0·008	0·003	8·6	3·5
H_2O^+	0·9	0·9	1·2	1·0	1·1	1·0	1·0	0·12	0·05	11·8	4·8
Fe°	1·6	1·6	1·6	1·6	1·6	1·5	1·6	0·04	0·02	2·8	1·1
Total	100·0	100·8	100·6	99·8	100·9	100·1	100·4	0·46	0·19	0·46	0·19

$\bar{x}$ = arithmetic mean.
S = standard deviation, the uncertainty of a single observation.
$S\bar{x}$ = standard error, the error of the arithmetic mean.
C = relative deviation of a single observation.
E = relative error of the mean.
Fe° denotes total Fe expressed as Fe_2O_3.
Locality: quarry at roadside, south-east corner of Dunglow Lough.

Table 4. Six analyses of T13—Older Granodiorite (dioritic phase) of Thorr District, Co. Donegal, Ireland

	1	2	3	4	5	6	$\bar{x}$	S	$S\bar{x}$	C	E
SiO_2	55·7	55·6	56·1	56·0	56·1	55·8	55·9	0·21	0·09	0·38	0·16
TiO_2	1·0	1·1	1·1	1·0	1·1	1·0	1·0	0·08	0·03	7·8	3·2
Al_2O_3	18·1	18·7	17·8	19·1	18·2	18·4	18·4	0·46	0·19	2·5	1·0
Fe_2O_3	1·6	1·6	1·5	1·4	1·6	1·7	1·6	0·11	0·04	6·8	2·8
FeO	4·3	4·3	4·3	4·3	4·2	4·2	4·3	0·06	0·03	1·5	0·60
MnO	0·08	0·08	0·08	0·08	0·08	0·08	0·08	0·003	0·001	3·5	1·4
MgO	3·5	3·3	3·3	3·4	3·3	3·3	3·4	0·10	0·04	2·9	1·2
CaO	5·4	5·5	5·5	5·5	5·5	5·5	5·5	0·04	0·02	0·81	0·33
Na_2O	4·5	4·6	4·6	4·6	4·5	4·5	4·6	0·08	0·03	1·7	0·69
K_2O	2·7	2·8	2·6	2·7	2·8	2·8	2·7	0·09	0·04	3·3	1·4
P_2O_5	0·39	0·39	0·38	0·39	0·38	0·39	0·39	0·006	0·003	1·6	0·66
H_2O^+	1·2	1·0	1·0	0·8	1·3	1·1	1·1	0·18	0·073	16·3	6·6
Fe°	6·4	6·4	6·3	6·2	6·3	6·4	6·3	0·09	0·04	1·4	0·58
Total	98·5	99·0	98·3	99·3	99·1	98·8	98·8	0·38	0·15	0·38	0·16

$\bar{x}$ = arithmetic mean.
S = standard deviation, the uncertainty of a single observation.
$S\bar{x}$ = standard error, the error of the arithmetic mean.
C = relative deviation of a single observation.
E = relative error of the mean.
Fe° denotes total Fe expressed as Fe_2O_3.
Locality: T13 is the bulked equivalent of two samples from the Owencrovarra River, south-east of Thorr.

FeO; of about 2·2 per cent for Al_2O_3; and between 4 and 8 per cent for TiO_2, Fe_2O_3, P_2O_5, and MnO; and of approximately 11 per cent for H_2O^+. Similarly, triplicate analyses would give values of E of less than 1 per cent for SiO_2, MgO, and CaO; between 1 and 2 per cent for Al_2O_3, FeO, Na_2O, K_2O, and total Fe; between 3 and 6 per cent for TiO_2, Fe_2O_3, P_2O_5, and MnO; and of approximately 8 per cent for H_2O^+.

As far as is known, there are no similar data with which these precision analyses can be compared. The nearest approach is to compare the statistical data of Tables 3 and 4 (one analyst, six determinations) with the data given in Table 17 of *Bull.* 980 (Granite G1, seven analysts, one laboratory; Diabase W1, six analysts, one laboratory). This is done in Table 5. Bearing in mind the differences in the

Table 5. Comparison of precision of rapid methods and conventional methods

	Granite M149–G1 type, 1 analyst, 6 determinations			Granite G1, American Standard, 7 analysts, 1 laboratory*			Diorite T13, 1 analyst, 6 determinations			Diabase W1, American Standard, 6 analysts, 1 laboratory*		
	$\bar{x}$	C	E	$\bar{x}$	C	E†	$\bar{x}$	C	E	$\bar{x}$	C	E†
SiO_2	73·4	0·46	0·19	72·64	0·31	0·12	55·9	0·38	0·16	52·66	0·64	0·26
TiO_2	0·21	6·0	2·5	0·25	11·2	4·2	1·0	7·8	3·2	1·03	4·15	1·7
Al_2O_3	14·2	3·5	1·4	14·13	1·22	0·46	18·4	2·5	1·0	14·87	3·23	1·3
Fe_2O_3	0·55	6·8	2·8	0·86	19·3	7·3	1·6	6·8	2·8	1·41	33·4	13·6
FeO	0·94	2·7	1·1	1·06	5·72	2·2	4·3	1·5	0·60	8·91	1·82	0·74
MnO	0·04	11·2	4·6	0·03	30·5	11·5	0·08	3·5	1·4	0·17	15·6	6·4
MgO	0·80	1·5	0·60	0·44	9·90	3·7	3·4	2·9	1·2	6·51	6·00	2·4
CaO	0·94	0·95	0·39	1·34	6·53	2·5	5·5	0·81	0·33	10·95	0·83	0·34
Na_2O	4·1	1·9	0·77	3·43	6·23	2·4	4·6	1·7	0·69	2·20	5·72	2·3
K_2O	4·2	2·8	1·2	5·43	3·83	1·4	2·7	3·3	1·4	0·68	7·06	2·9
P_2O_5	0·09	8·6	3·5	0·10	23·4	8·8	0·39	1·6	0·66	0·15	18·7	7·6
H_2O^+	1·0	11·8	4·8	0·31	26·7	10·1	1·1	16·3	6·6	0·45	10·5	4·3
Fe°	1·6	2·8	1·1	2·04	9·30	3·5	6·3	1·4	0·58	11·30	3·92	1·6

* U.S. Geological Survey Laboratory. Figures for $\bar{x}$ and C taken from Table 17, p. 38 *U.S. Geol. Surv. Bull.* 980.

† Calculated from $E = C/\sqrt{n}$ on the basis $n = 7$ (granite) and $n = 6$ (diabase).

$\bar{x}$ = arithmetic mean.

C = relative deviation of a single observation.

E = relative error of the mean.

Fe° denotes total Fe expressed as Fe_2O_3.

methods of analysis and that one set of figures represents the work of six or seven analysts, it is reasonable to conclude that the rapid methods give results comparable in precision to those given by conventional methods, and in some cases the results are decidedly superior, e.g., in the case of MgO, CaO, Na_2O, P_2O_5, and total Fe.

Another comparison that can be made is with the spectroscopic data for Al_2O_3, total Fe, MnO, MgO, and CaO given in Table 11 of *Bull.* 980. The relevant figures

Table 7. Duplicate determinations for the major elements

	SiO_2			Al_2O_3			FeO			MgO			CaO			Na_2O			K_2O			Fe°		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
M7	73·3	74·1	1·1	15·1	14·6	3·4	0·63	0·68	7·6	0·50	0·57	13	0·95	0·94	1·1	3·9	4·0	2·5	4·7	4·8	2·1	1·2	1·2	0
M17	73·5	72·9	0·8	13·3	14·1	5·8	0·67	0·72	7·1	0·52	0·62	18	0·80	0·76	5·1	4·1	3·8	7·5	4·8	4·6	4·2	1·4	1·4	0
M27	74·6	75·5	1·2	13·7	13·5	1·5	0·31	0·26	18	0·16	0·21	28	0·15	0·11	31	3·5	3·4	2·9	6·3	6·3	0	0·58	0·62	6·7
273	75·3	75·1	0·3	13·4	14·0	4·4	0·62	0·60	3·3	0·40	0·39	2·5	0·72	0·69	4·3	4·1	3·9	5·0	4·4	4·5	2·3	1·1	1·1	0
M49	73·8	74·2	0·5	13·6	13·4	1·5	0·70	0·76	8·2	0·44	0·43	2·3	0·50	0·50	0	4·0	4·2	4·9	4·9	4·9	0	1·3	1·2	8·3
M62	73·8	73·6	0·3	13·7	13·6	0·7	0·89	0·92	3·3	0·55	0·55	0	0·92	1·00	8·3	3·6	3·9	7·9	5·0	5·4	7·7	1·4	1·4	0
M75	76·1	76·0	0·1	12·8	13·4	4·6	0·24	0·19	23	0·16	0·15	6·2	0·51	0·49	4·0	3·9	3·5	10·8	4·5	4·3	4·5	0·52	0·52	0
M90	71·2	71·1	0·1	14·5	13·9	4·2	1·2	1·3	8·3	1·1	1·0	10	1·6	1·6	0	4·0	4·2	4·9	5·0	4·5	10·4	2·3	2·2	4·5
M100	75·2	75·5	0·4	13·9	13·3	4·4	0·20	0·25	23	0·18	0·14	25	0·42	0·45	6·8	4·1	3·9	5·0	4·7	5·1	8·2	0·49	0·48	2·1
M113	76·7	77·4	0·9	12·6	13·0	3·1	0·25	0·26	3·8	0·22	0·13	50	0·52	0·48	8·0	4·0	4·2	4·9	5·0	5·0	0	0·54	0·54	0
M125	75·5	75·6	0·1	13·5	13·5	0	0·52	0·48	8·0	0·28	0·36	25	0·86	0·84	2·4	4·1	4·0	2·5	5·0	4·6	8·3	0·90	0·91	1·1
M136	61·6	61·7	0·2	18·1	17·6	2·8	5·4	5·4	0	5·2	5·1	1·9	0·48	0·56	15	0·88	0·92	4·4	3·4	3·7	8·3	6·5	6·6	1·5
T1	67·2	66·8	0·6	15·7	15·3	2·6	2·2	2·2	0	1·5	1·6	6·2	2·3	2·3	0	4·3	4·4	2·3	4·8	4·7	2·1	3·4	3·6	5·7
T11	64·2	64·2	0	16·7	15·9	4·9	2·7	2·8	3·6	1·7	1·8	5·6	3·2	3·2	0	4·3	4·4	2·3	4·3	4·2	2·4	3·7	4·0	7·9

Columns *a* are single determinations done at time *a*.
Columns *b* are single determinations done at time *b*.
Columns *c* are the per cent differences between *a* and *b*.
For Si, Al, twenty-four hours separate times *a* and *b*.
For FeO, Mg, Ca, Na, K, Fe°, seventy-two hours separate times *a* and *b*.
Fe° denotes total Fe expressed as Fe_2O_3.

are given in Table 6. It is obvious that the rapid methods for Al_2O_3, total Fe, MnO, MgO, and CaO are more precise than these particular spectroscopic methods; and, in particular, the errors of single determinations are far less.

Table 6. Comparison of precision of rapid methods and spectroscopic methods

	Granite M149–G1 type 1 analyst 6 determinations			Granite G1 American Standard 1 analyst* 9 determinations			Diorite T13 1 analyst 6 determinations			Diabase W1 American Standard 1 analyst* 12 determinations		
	$\bar{x}$	C	E	x	C	E	$\bar{x}$	C	E	x	C	E
Al_2O_3	14·2	3·5	1·4	14·44	4·7	1·6	18·4	2·5	1·0	15·23	5·8	1·7
Fe°	1·6	2·8	1·1	2·04	4·7	1·6	6·3	1·4	0·58	11·30	6·2	1·8
MnO	0·04	11·2	4·6	0·03	12·4	4·1	0·08	3·5	1·4	0·19	9·0	2·6
MgO	0·80	1·5	0·60	0·39	6·5	2·2	3·4	2·9	1·2	6·52	6·7	1·9
CaO	0·94	0·95	0·39	1·42	4·6	1·5	5·5	0·81	0·33	10·95	5·8	1·7

* W. H. Dennen, Massachusetts Institute of Technology, spectroscopic data taken from Table 11, p. 28, *U.S. Geol. Surv. Bull.* 980.
x = concentration.
$\bar{x}$ = arithmetic mean.
C = relative deviation of a single observation.
E = relative error of the mean.
Fe° denotes total Fe expressed as Fe_2O_3.

6. Duplication over an Extended Period of Time

Tables 7 and 8 give the results of duplicate analyses of fourteen granitic rocks. These analyses were obtained during a period of eight months and may be said to be a guide to the overall precision of the rapid methods when analysing a large number of rocks under routine conditions.

Table 8. Duplicate determinations for the minor elements and totals

	Fe_2O_3			TiO_2			MnO			P_2O_5			H_2O^+			Totals		
	a	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*	*a*	*b*	*c*
M7	0·50	0·45	10	0·17	0·15	12	0·04	0·04	0	0·04	0·06	40	0·6	0·5	18	100·4	100·9	0·5
M17	0·66	0·60	9·5	0·20	0·20	0	0·03	0·03	0	0·06	0·09	38	0·7	0·7	0	99·3	99·1	0·2
M27	0·24	0·33	32	0·04	0·04	0	0·04	0·05	25	0·02	0·02	0	0·7	0·5	33	99·8	100·2	0·4
273	0·41	0·43	4·8	0·14	0·16	13	0·03	0·03	0	0·05	0·04	25	0·8	0·9	12	100·4	100·7	0·3
M49	0·52	0·36	36	0·16	0·16	0	0·03	0·06	75	0·02	0·04	67	1·0	0·8	22	99·7	99·8	0·1
M62	0·41	0·38	7·5	0·19	0·16	17	0·02	0·02	0	0·08	0·09	12·5	0·4	0·6	40	99·6	100·2	0·6
M75	0·25	0·31	21	0·08	0·06	29	0·03	0·03	0	0·04	0·04	0	0·6	0·6	0	99·2	99·1	0·1
M90	0·97	0·76	24	0·15	0·15	0	0·04	0·02	67	0·11	0·10	10	0·5	0·8	46	100·4	99·4	1·0
M100	0·27	0·20	29	0·06	0·05	17	0·03	0·02	50	0·01	0·03	100	0·6	0·6	0	99·7	99·5	0·2
M113	0·26	0·25	3·8	0·12	0·14	15	0·01	0·02	50	0·01	0·03	100	0·3	0·5	50	100·0	101·4	1·4
M125	0·32	0·38	17	0·14	0·11	25	0·04	0·04	0	0·04	0·04	0	0·6	0·6	0	100·9	100·6	0·3
M136	0·51	0·61	18	0·80	0·78	25	0·04	0·03	25	0·11	0·11	0	0·8	0·9	12	97·3	97·4	0·1
T1	0·96	1·2	22	0·61	0·57	6·8	0·06	0·06	0	0·22	0·21	4·5	1·0	1·0	0	100·8	100·3	0·5
T11	0·70	0·89	24	0·63	0·69	9·1	0·04	0·05	25	0·27	0·26	3·8	0·8	0·8	0	99·5	99·2	0·3

Columns *a* are single determinations done at time *a*.
Columns *b* are single determinations done at time *b*.
Columns *c* are the per cent differences between *a* and *b*.
For Fe_2O_3, TiO_2, MnO, and P_2O_5, seventy-two hours separate times *a* and *b*.
For H_2O^+, twenty-four hours separate times *a* and *b*.

In general, the results are very satisfactory despite the tendency for the error to increase with decrease in concentration (see, for example, the figures for MgO and CaO). The large error in the determination of Fe_2O_3, and the apparent failure of the method for P_2O_5 at very low concentrations ($<0{\cdot}05$ per cent), should be noted. The occurrence of large errors in the determination of alkalies (three cases for Na_2O; five cases for K_2O) is disappointing; the precision of flame photometry may be increased by the use of the simpler techniques mentioned in Part 4 of this paper.

7. Conclusions

The accuracy and precision of the rapid methods of Shapiro and Brannock (1952), modified as indicated above, compare very favourably with both conventional chemical and with spectrographic procedures. For most petrological purposes their precision is adequate. They are ideally suited for serial analyses of a rock complex, and in such a case single analyses of individual rock samples will give the required comparative data with known precision. It is advisable in such studies to repeat about 10 per cent of the analyses. The methods are also suitable for odd analyses of silicate rocks, but such analyses should be in duplicate at least. Great precision may be obtained by repeating an analysis four or more times, and such precision may be as good as, if not better than, that obtainable by conventional chemical methods.

Since several geological departments in British universities have indicated their intention of using the rapid methods, it may be advantageous to indicate appropriate lines of research:—

(1) The extension of the methods to include all classes of silicate rocks.

(2) The adaptation of the methods to carbonate rocks.

(3) The choice of adequate standard rocks.

(4) The preparation of an artificial standard of known composition.

(5) A co-operative investigation of inter-laboratory accuracy and precision, using the standards mentioned in (3) and (4).

Research of this type is planned for the immediate future in the Department of Geology, Imperial College.

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Terrestrial helium

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Abstract—The problem of terrestrial helium is considered in the light of the measured isotopic abundance ratio of helium in the atmosphere.

It appears from new evidence now available that the rate of release of He^4 to the atmosphere from the earth's crust is about sixty times greater than previous estimates. Thus, in order to maintain the atmospheric helium isotopic abundance ratio, the production of He^3 in the atmosphere must be considerably greater than that already calculated on the basis of cosmic-ray induced (n,H^3) reactions on nitrogen (even in the limiting case of equal escape probabilities for the two helium isotopes). The extra-terrestrial dust, which is continuously accreted by the earth, is considered as a source of He^3, and an estimate is made of the amount which is required to be collected per day, on the basis of recent work on meteoritic material. An infall of about 5000 tons per day for the whole earth is indicated; this figure depends on the history of the dust particles.

The origin of the dust is considered; and the desirability of making a collection of this cosmic dust is discussed.

Introduction

There is good reason to believe that the present-day atmosphere of the earth is of secondary origin; in the process of planet accretion the volatile components, including the rare gases, are likely to have been largely lost from the primitive earth (Brown, 1952; Suess, 1949) and the present atmosphere mainly developed by a process of degassing and weathering throughout the geological life of the earth.

A measure of the extent of the original loss for a particular element is given by its fractionating factor, which is defined as the ratio of the abundance of the element to that of silicon as estimated for the universe, divided by the value of this ratio as observed on earth. (Silicon is used as a comparative standard as it forms stable nonvolatile compounds.) The values of the fractionating factor for the rare gases, as estimated by Brown (1952), are given in Table 1. This is based on data concerning the composition of the atmosphere by Paneth (1937) also included in the table, together with data by Rayleigh (1939), Cady (1945), and Brown (1949). The value of the fractionating factor which is given for argon is based on the abundance of A^{36} only, because although the greater proportion of terrestrial argon is A^{40}, some 99·57% (Nier, 1952), this isotope is thought to be

Table 1

	Fractionating factor		Atmospheric abundance	
	Maximum	Minimum	p.p.m. by vol	Total mass $\times 10^{15}$ g
He		(10^{14})	5·2	3·7
Ne	$5 \cdot 10^{10}$	$7 \cdot 10^{9}$	18	63·6
A	$8 \cdot 10^{8}$	$2 \cdot 10^{8}$	9300	65,500
Kr	$3 \cdot 10^{7}$	$3 \cdot 10^{6}$	1	14·6
Xe	$8 \cdot 10^{6}$	$7 \cdot 10^{5}$	0·08	1·8

relatively less abundant than A^{36} cosmically. The bulk of the abnormally high-terrestrial argon abundance must then be radiogenic A^{40}, as first suggested by von Weizsäcker (1937), and later confirmed by many workers. The value given in parentheses for helium is certainly subject to correction. But it is difficult to see how correction can be made, because both of its stable isotopes are produced continuously in nuclear reactions on the earth, and the situation is further complicated by the continuous escape of helium from the earth's gravitational field. One might, however, estimate the true fractionating factor by extrapolating to low atomic mass-number the data for the other rare gases; the result is a fractionating factor several orders of magnitude greater than that given in the table. There seems to be little doubt that practically all of the primordial helium was lost, and that present-day terrestrial helium is the result of nuclear disintegrations during the lifetime of the earth. The problem presented by terrestrial helium is one of striking a balance between the rates of generation and of escape for two isotopes whose origins are entirely unrelated. We shall show that, assuming the probability of escape from the atmosphere of He^3 is at least as great as that for He^4, the presently-proposed mechanisms for the generation of He^3 are quantitatively inadequate to maintain the isotopic-abundance ratio of helium found in the atmosphere, where $He^3/He^4 \sim 1{\cdot}2 \cdot 10^{-6}$ (Aldrich and Nier, 1948). Much of the geochemical data is not precise, so we are primarily interested in orders of magnitude only.

Crustal Erosion

Rock weathering will release the gases occluded in the crust to the atmosphere. An early estimate of the amount of weathered rock, based on the Na content of the oceans (Clarke, 1924), gave a value of $8{\cdot}33 \cdot 10^{23}$ g, and this was substantiated by other estimates (Lindemann, 1939; Goldschmidt, 1933), although Kuenen (1950) believes that this represents less than half of the total. Lindemann has calculated the minimum amount of He^4 thus released in 10^9 years to be about $2 \cdot 10^{17}$ g, or $1{\cdot}5 \cdot 10^5$ atoms He/cm^2 sec for the whole of the earth's surface.

This cannot be the main source of supply of the rare gases to the atmosphere. Rayleigh (1939) has given the average neon content of present-day crustal rock as $8 \cdot 10^{-8}$ cm^3 Ne/g; and the average argon content as $2 \cdot 10^{-5}$ cm^3 A/g. However, there is reason to believe that rocks may lose a fraction of their gas, at least if it is radiogenic, a loss which is to be distinguished from rock-weathering. (In determining the branching ratio of K^{40} by measuring the amount of A^{40} produced in geologically well-dated mineral samples, values of the branching ratio of 0·085 have been calculated, while the value found by counting techniques is 0·125; the difference could be explained by assuming a 40% loss of A^{40} from the mineral specimens.) Nevertheless, even taking Kuenen's estimate of the rock-erosion, and assuming the unleached value of argon content is about $4{\cdot}5 \cdot 10^{-5}$ cm^3/g, less than 1% of the atmospheric abundance of these gases can be attributed to erosion of rock of present-day gas content. Furthermore, most of the terrestrial argon and neon are in the atmosphere, less than 2% in either case residing in the crust, at the most generous estimate. Clearly the atmosphere either had a contribution from the primordial gas (or from a rapid degassing as the earth became large enough to

retain an atmosphere); or it has been heavily reinforced from subcrustal regions: or the crust is being continuously degassed, right up to the present day.

Crustal Degassing

The first suggestion must be dismissed on the grounds both of the large fractionating factor and the fact that A^{40}, which forms 99·57% of terrestrial argon, is cosmically scarce compared with A^{36} and A^{38}. The second possibility has been worked out in detail by Kulp (1951), who estimated that only about 15% of the A^{40} has been leached out of the crustal rocks, the remainder coming from the mantle. However, new estimates of the potassium content of the mantle (Ahrens *et al.*, 1952; Holyk and Ahrens, 1953) have suggested that this is an unlikely source of the argon.

The last possibility, that the crust is being continuously degassed, appears the most acceptable. It is inherent in Wilson's (1954) ideas regarding the formation of continental masses by successive additions of volcanic material about central nuclei; one assumes that as the lava is exposed in the molten state it is completely degassed. Since the process of orogeny appears to be a continuous one (Wilson, 1952), the crustal degassing is continuous. Also, on this basis, Shillibeer and Russell (1955) calculated the age of the earth, using current estimates of the potassium content of rocks, and the crustal structure. They find an (upper) value of $5{\cdot}3 \cdot 10^9$ years, which would be lowered to about $4{\cdot}8 \cdot 10^9$ years by using a branching ratio of potassium of 0·125. This is in good agreement with estimates of the age from other evidence.

The fact that there is this high gas-loss from the crust does not mean that those methods of rock-dating, which depend on estimating the amount of gaseous daughter-element produced in a mineral during its lifetime, are inapplicable. The geological age so measured is just that time since the specimen last cooled to such an extent as to be able to retain gas. In fact, there may be additional loss of gas due to leakage even after this cooling. The discrepancy in the measured values of the branching ratio has already been mentioned as indicating such a loss to the extent of about one-half of the radiogenic argon in some potassium minerals Hurley (1954), who made a study of the distribution and migration of helium in rocks, concluded that, because of radiation damage to the crystal structure in the vicinity of radioactive concentrations, a considerable fraction of the helium in many cases is made "mobile;" and this may migrate to the surface. He has estimated that as much as 10^9 atoms He/cm^2 sec of this mobile helium may leak from the crust, even in stable crystalline areas. Fresh samples taken from a depth of 1 km have shown a loss of four-fifths of their helium. However, the contribution of leakage losses to the atmosphere is relatively unimportant.

The sum of these loss-effects is, to a sufficient approximation, to leach continuously the crust almost entirely of its radiogenic gases. The rate of release of these gases is then just equal to their rate of generation in the crust, with a relatively small hold-up there.

Helium in the Crust

The rate at which He^4 is generated in the crust is determined by the U and Th content of the rocks. Birch (1954) summarized all of the available data on the

radium content of granitic and basaltic rocks, and from this information it has been deduced (assuming a Th : U ratio of 3·5) that helium production in these rocks is approximately $3{\cdot}5 \cdot 10^{-3}$ cm^3/g and $0{\cdot}5 \cdot 10^{-3}$ cm^3/g respectively in 10^9 years. In the crustal model which has been used successfully by Shillibeer and Russell, and which is essentially in agreement with the findings of Hess (1954) and Bullard (1954), the mass of the (granitic) continental blocks is $15 \cdot 10^{24}$ g; the mass of basalt to a depth of 5 km underlying the continents and the oceans is $7{\cdot}5 \cdot 10^{24}$ g. One might prefer a greater mass of basalt in order to increase the ratio of basalt: granite, and to increase the total mass of the crust. However, the contribution per gram of basaltic rock to the helium production is about seven times less than that of granitic rock, so that doubling the mass of basalt will have little effect on the calculation. Using the model of Shillibeer and Russell, the rate of He^4 production in the crust turns out to be $95 \cdot 10^5$ atoms He^4/cm^2 sec for the whole of the earth's surface. If this is equal to the rate of liberation of helium from the crust, it is about sixty times greater than the original estimate based on rock-erosion. This does not imply, however, that the total rock weathered to produce sedimentary rock is also greater by this factor. Rankama (1954) estimated the weathering of igneous rock to be forty times greater than the original erosion figures.

He^3 is produced continuously in the crust by a thermal neutron reaction on Li^6 (Hill, 1941).

$$Li^6(n, \alpha)H^3 \rightarrow He^3.$$

The neutrons are assumed to result from the spontaneous fission of U, and from (α, n) reactions on the light-element constituents of common rock. Inghram (1953) gave the order of magnitude of the average neutron production as about 10^{-7} n/g sec in ordinary rock. Since the efficiency for utilization of these neutrons in the Li reaction is about 1% the He^3 production is of the order of $5 \cdot 10^{-2}$ atoms He^3/g rock-yr. Hence the average isotopic ratio He^3/He^4 in the crust is about $1 \cdot 10^{-9}$. This is equivalent to the release of 10^{-2} atoms He^3/cm^2 sec from the crust, assuming He^3 to have the same probability of release as He^4. Thus the liberation of He^3 from the crust makes a negligible contribution to the atmosphere.

Helium in the Atmosphere; the Helium Isotopic Balance there

The abundance of He^4 in the atmosphere is determined by its rate of release from the crust and the rate of its escape from the earth's gravitational field. If it is assumed that the atmosphere is now in equilibrium with respect to helium abundance, then the escape rate must be equal to the crustal liberation rate calculated above, viz. approximately 10^7 atoms He^4/cm^2 sec. The probability of escape (see, e.g., Jeans, 1916) of He^3 must be at least as great as that of He^4. In fact, one might expect it to be considerably greater because of its smaller mass permitting He^3 to escape more readily from the exosphere, and to diffuse upwards through the atmosphere more easily; at 1500° about an order of magnitude greater. The difference of escape probabilities, however, may be very little if the controlling factor in the escape process is the mechanism proposed by Spitzer (1948), who has suggested that escape will take place mainly during those brief intervals

when the temperature of the upper atmosphere rises to over 2000°, following an excessive burst of solar ultra-violet radiation. Under these conditions of high temperature, the exosphere is rapidly emptied of both helium isotopes, and the limiting factor in escape is diffusion of helium to the outer atmosphere. The mechanism also permits the larger escape rate required, while maintaining the average temperature of the upper atmosphere at something less than 1500°, a condition which is made necessary by observations of the forbidden red line of oxygen there.

If we assume the escape probabilities for the two isotopes are the same, since the atmospheric helium-isotope ratio He^3/He^4 is maintained at about $1{\cdot}2 \cdot 10^{-6}$, the rate of escape of He^3 is approximately 10 atoms He^3/cm^2 sec; and this must be the rate of production of He^3 also.

H^3 is generated in the atmosphere by fast-neutron reactions (Libby, 1946)

$$N^{14}(n, H^3)C^{12},$$

$$N^{14}(n, H^3)3\alpha,$$

and in those nuclear events which appear as "stars" in photographic emulsions; all these are induced by cosmic radiation. H^3 rapidly decays to He^3. Fireman (1953) has calculated the total rate of production of He^3, both by these processes and directly in stars, to be about 1·5 atoms He^3/cm^2 sec. Although his estimate accounts adequately for the measured H^3 content of terrestrial waters, it is an order of magnitude too low to account for the atmospheric He^3. Production in the crust cannot be much greater than a factor 10 over that calculated above, otherwise Ne^{21} produced in the reaction $O^{18}(\alpha, n)Ne^{21}$, which has been proposed as a source of neutrons in the crust, would be unaccountably large. Furthermore, from C^{14} data it appears unlikely that the cosmic-ray flux at the earth has suffered any large variation, for the last 30,000 years at least; the atmosphere is in equilibrium in respect of cosmic-ray effects. Thus we require to identify another source of He^3, which to a sufficient approximation will supply 10 atoms He^3/cm^2 sec to the atmosphere.

Rate of Accretion of Extra-terrestrial Dust by the Earth

Such a source may be found in the extra-terrestrial dust which the earth is continuously collecting. Recent work on meteoritic matter has shown that there is a considerable amount of He^3 produced in it by the action of cosmic radiation (Paneth *et al.* 1952, 1953; Reasbeck and Mayne, 1955). Quantities of about 10^{-5} cm^3 He^3/g iron have been detected in the outer layer of iron meteorites which have been subject to the full effects of the cosmic radiation during their flight in space. Small grains of material ought to have twice this amount; and further, if the ideas regarding the young age of iron meteorites prove correct (Dalton *et al.*, 1953), or if the cataclysmic break-up of their parent planet took place about 10^8 years ago, the effect in the dust particles may be ten times greater. A precise estimate of the mass of dust which would have to be accreted is difficult to make, because the production rate of He^3 in silicate meteoritic material has not been fully explored; it is probably not greatly different from that in iron. However, considering only the collection of iron dust, using a figure of $3 \cdot 10^{-5}$ cm^3 He^3/g.

the accumulation rate required would be 5000 tons a day; even if the generation rate in silicate is five times less than that in iron, the figure of 10,000 tons a day is probably a reasonable (upper) estimate to the total infall. This estimation assumes that the total irradiation (cosmic-ray flux $\times$ time) is the same for the dust as for the iron meteorites. If the dust has experienced radiation more intense or for a longer time, then 10,000 tons a day would be an outside estimate. If the escape rate of He^3 is much greater than that of He^4, the daily infall would have to be greater than 10,000 tons. A precise determination of the pre-atmosphere amount of He^3/g of dust would settle the first point; and together with a measurement of the total daily infall would decide the second.

The Origin of the Dust, and Its Identification

The dust considered in this calculation may correctly be called cosmic. It cannot be debris of the original collision which gave birth to the meteorites, or of any subsequent collision of the fragments of that catastrophe. The lifetime with respect to spiralling into the sun, on account of the Poynting-Robertson effect, is given by $t = 7 \cdot 10^6 \; s.a.q. \; \rho$ years, where s is the radius of the dust particle in cms, ρ its density in g/cm^3, and a and q the semi-major axis and perihelion distance respectively of the initial orbit of the particle (Wyatt and Whipple, 1950). This lifetime is certainly too short a period for the cosmic radiation to produce the effects upon which the calculation is based. for asteroidal debris particles (assuming a density of 5) of less than 1000 μ diameter.

The origin of the dust is less certain. Van de Hulst (1947) has considered the effects of light scattering from a quiescent haze of small dust-particles in the plane of the ecliptic in order to explain the zodiacal light. Assuming a density of 5 for the material of this dust, he has estimated the space density due to dust particles up to 700 μ diameter (almost all of the particles are smaller than this limit) to be $5 \cdot 10^{-21}$ g/cm^3 in the neighbourhood of the earth. If the earth sweeps this cloud of density ρ with a relative velocity v, the rate of collection of material is given by

$$\frac{dM}{dt} = \pi r^2 v \rho + \frac{2\pi G M r \rho}{v} + \frac{10 G^2 M^2 \rho}{v^3}$$

where M is the mass of the earth of radius r, and G is the gravitational constant. The first term is just the geometrical cross-section contribution; the second (Eddington, 1926) represents the gravitational attraction; the third takes account of the slip-stream mechanism of Hoyle and Lyttleton (1941) which must be included when the density ρ is greater than 10^{-22} g/cm^3. The contribution of each factor to the total amount accreted is given in Table 2, from which it is seen that the accumulation rate is not strongly dependent on the velocity of approach. One would expect that if the dust is also circulating, the velocity of approach is less than that of the earth in its orbit (30 km/sec), with a lower value of 10 km/sec (i.e., the escape velocity of the earth); this gives an accretion rate close to that calculated above. Then it would not be unreasonable to suggest that the cosmic dust collected is just the interplanetary dust associated with the zodiacal light. Since this is distributed along the ecliptic, the cosmic dust probably

Table 2

Velocity of approach	$\pi r^2 v \rho$	$\frac{2\pi GMr\rho}{v}$	$\frac{10G^2M^2\rho}{v^3}$	Total tons/day
30 km/sec	1550	220	26	1800
10 km/sec	520	660	700	1880

represents the primordial building material of the solar system, left over in the outer regions after the planets formed, and now spiralling in towards the sun under the influence of the Poynting-Robertson effect. There may also be another component in the dust, swept up by the earth from the meteor showers which it encounters. This contribution, being sporadic and following on the well-known periods of meteor activity, is likely to show up as bursts of high infall-rate superimposed on the interplanetary dust-collection background. However, this source of dust is not likely to make any contribution to the terrestrial helium supply: since the comets move in extremely eccentric orbits, the associated meteor streams must have been thoroughly degassed at their perihelion transit. (Nevertheless, it would appear desirable to measure the contribution of this meteor debris to the total mass of dust accretion, for example by making collections of the bursts; in this way the cosmic-dust component of the total dust collection over a long period of time, as, e.g., that found in permanent snows, can be estimated.)

The total rate of deposition of dust has also been estimated by Pettersson and Rotschi (1952) from observations of the relatively high Ni content of deep-sea cores. Assuming a Ni content of cosmic dust of 2% by weight, they gave an accumulation rate of several thousand tons a day. The basis of the estimate has been criticized by Smales and Wiseman (1955), however, on the grounds that the Cu/Ni and Co/Ni ratios in these cores are essentially terrestrial. Öpik (1955) has recently pointed out that this may not be a valid criticism.

The collection of samples of cosmic dust is interesting both for geochemical and astrophysical reasons. The dust probably represents the undifferentiated building material of the planets; so a study of its composition would put the geochemistry of planet formation on a more certain foundation. An analysis of the distribution of particle size of the dust would provide information on its astrophysical history; for this distribution is determined not only by the original distribution in space, but also by the passage of the dust particles through the atmosphere, i.e., their relative speed of approach to the earth. Van de Hulst has already given the distribution of particle size in space for the dust associated with the zodiacal light.

There have been several attempts in the past to make such a collection (Buddhue, 1950), the chief difficulties being to reduce terrigenous contamination to a relatively low level, and to identify positively the cosmic material. No attempt has been made to estimate the contribution of meteor debris to the total dust. We have here estimated the rate of sedimentation of interplanetary dust to be about 10^{-9} g/cm^2 day. Some of this should reach the earth's surface without

degassing. WHIPPLE (1950, 1951) has shown that, if the particles of dust are small enough, they can pass through the atmosphere without melting. Particles of 25 μ diameter would have to travel faster than 11 km/sec before they melted. The average velocity of approach of zodiacal dust particles is probably not much greater than this value, the escape velocity, if the dust is circulating along with the earth; and the number of particles of a given diameter increases rapidly with decreasing diameter. Hence the retention of helium in the interplanetary dust material should be high. We propose to identify cosmic dust by examining the isotopic composition and abundance of the occluded helium in freshly collected samples. This will provide a more positive test than the usual method based on the relative abundances of Ni and Fe. If 10% of the helium remains intact, a 10-mg sample of dust would be sufficient for isotopic analysis. Also, with this amount of sample material one can study the total helium retention in particles of different size-range (CHACKETT *et al.*, 1953; PANETH, 1953), in order to estimate the total helium content of the dust before it entered the earth's atmosphere. This then permits an estimation of the average velocity of approach of the dust.

The most suitable place on earth to make a cosmic-dust collection is in the region of permanent anti-cyclonic conditions in Antarctica, where terrigenous contamination should be a minimum. With the calculated infall of dust, and assuming a 300-cm snowfall per annum, 1 m^3 of snow should contain 1 mg of cosmic dust. Because the polar region is climatically arid, and due to the fact that some of the snow evaporates during the summer, this figure for the dust content is probably a low one. We hope it may be possible to carry out some dust collections in Antarctica during the geophysical year.

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The production of chlorine-39 in the lower atmosphere by cosmic radiation*

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Abstract—Examination of rain-water has revealed the presence of chlorine-39 formed by the interaction of cosmic radiation with argon in the lower atmosphere. The maximum amount of activity found agrees with what is expected from known reactions of cosmic radiation. Most of the production of chlorine-39 is due to the reaction

$$A^{40} + \mu^- = Cl^{39} + n + \nu.$$

In several cases little activity was found. This appears to result from meteorological phenomena. Chlorine-39 is potentially useful in meteorology with specific application to the study of rain.

IT is known that carbon-14, tritium, and beryllium-7 are produced by cosmic radiation in the upper atmosphere (ANDERSON *et al.*, 1947; FIREMAN, 1953; KAUFMAN and LIBBY, 1954; ARNOLD and AL-SALIH, 1955). The relatively long half-lives of these nuclides enable atmospheric mixing to bring them into contact with the lower atmosphere, from which they can be extracted by natural processes such as precipitation of rain and snow and the absorption of carbon dioxide by plants. Many other radioactive nuclides are undoubtedly formed in the upper atmosphere, as shown by examination of photographic plates exposed at high altitudes (CAMERINI *et al.*, 1952). However, most of these nuclides are relatively short-lived, and hence decay in the vicinity of their formation. In order to detect any of these at the earth's surface, they must have been formed in the lower atmosphere.

Among the many nuclides of this type are 33*m* Cl^{34}, 37*m* Cl^{38}, and 56*m* Cl^{39}, from the interaction of cosmic radiation with atmospheric argon. These atoms are born in a highly excited state and lose their energy by emission of gamma-rays and by collisions with air molecules. They finallly enter into simple combinations with oxygen and nitrogen or end up as the chloride ion. These should all be readily extracted from the air during a rain. They can then be separated and measured by radiochemical means.

PROCEDURE

The rain-water was collected in the Weizmann Institute housing area from four roofs which had a sufficient slope to ensure rapid drainage. The total area in horizontal projection was 450 square metres. The water from the beginning of the rain was collected at fourteen drains by means of bottles which permit the collection of the desired amount of water and allow the rest to overflow without diluting the initial sample. Because of holdback in several of the drains resulting from unevenness or slope in the wrong direction, the actual area of collection was approximately 300 square metres.

To the total of 5 litres of rain-water thus collected was added a carrier solution of sodium chloride standardized at 288-mg silver chloride. In a few cases carrier was not added, because a certain amount of chloride is always present as salt-spray from the nearby Mediterranean Sea.

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The water was then filtered to remove dirt and sand, and silver nitrate solution was added. The silver chloride precipitate was separated by a large Hearson centrifuge, which can handle 1·8 litres at a time. Ammonium hydroxide was added to the precipitate, and the mixture heated to bring silver chloride into solution. Lanthanum carrier was added to bring down insoluble hydroxides, strontium to remove carbonate, and iodide to precipitate silver iodide. The mixture was centrifuged and filtered. More silver nitrate was added. The solution was finally acidified with nitric acid to precipitate silver chloride, which was mounted and counted with a thin-window methane-flow proportional counter. The entire procedure required two to two and a half hours. The chemical yield was close to 100% (a possible exception being experiment 3 of Table 1).

Results

The results of five experiments performed in the above manner are given in Table 1. The work was terminated by the end of the rainy season in Israel. In the second column of the table is given the time the sample was collected. The rain usually continued for at least an hour more. In the next column is given the height of the base of the rain cloud as estimated at several nearby meteorological stations. In the fourth column is indicated whether sodium chloride solution was added. The final weight of silver chloride as mounted for counting is given in the fifth column.

The activity of the sample was followed until it reached a steady value. Because of the operational stability and low background (8·0 $\pm$ 0·2 c.p.m.) of the counter, the counting accuracy was essentially limited by the statistical error. The long-lived residual activity was approximately one count per minute in the first four experiments, and 14 c.p.m. in the last. The half-life of the latter was of the order of several months, and was probably due to contamination from various nuclear explosions which have been tested lately. A slight amount of brown material in colloidal suspension persisted through the separation procedure and appears to have carried the contamination.

The only component remaining after the subtraction of the background and the long-lived residual activity is that indicated in the sixth column of Table 1. In experiments 1 and 5 this component was followed for three or four hours with the half-life indicated in the last column. There was insufficient activity in the other experiments for a half-life determination of this component. However, the decay of these was not inconsistent with the half-lives obtained in experiments 1 and 5. The half-lives found agree with that of 56*m* Cl^{39} within experimental error. No nuclide with a similar half-life and a long-lived parent is known. It is, therefore, very unlikely that this component was due to contamination.

The activity of chlorine-39 in experiments 1 and 5, extrapolated to the time of rain collection, was 50 c.p.m. Corrected for counting efficiency, this corresponds to a disintegration rate of approximately 500 per minute. The combined activity of chlorine-34 and -38 must have been less than this amount at collection time to escape detection.

Discussion

In order to account for the activities of chlorine-39 given in Table 1, it is necessary to examine (1) the processes by which this nuclide is formed in the atmosphere, and (2) the processes by which it is removed from the atmosphere. It is convenient to divide the processes by which chlorine-39 can be formed into

those initiated by slow negative muons and those by other components of cosmic radiation. In both cases the target-element is argon. No other constituent of the atmosphere which might contribute to the formation of chlorine-39 is present in a significant concentration.

Table 1. Data from experiments on chlorine activity in rain-water

Exp	Time of collection (1955)	Height of base of rain-cloud (m)	Carrier added	Wt Ag Cl (mg)	Activity (c.p.m.)	Half-life (min)
1	0830–0900 March 16	600	yes	2116	8	65 ± 15
2	0845–0900 March 18	750	yes	513	1–2	
3	1520–1530 March 26	1050	no	49·3	1–2	
4	2320–2325 March 27	750	no	221	1–2	
5	1230 –1300 April 6	900	yes	786	10	60 ± 10

The method of delayed coincidences permits the measurement of the decay of slow muons as a function of the atmospheric depth, Fig. 7 of Rossi (1948). The rate of nuclear reaction of negative muons with atmospheric argon can be derived from this curve, with the following information (Thorndike, 1952; Sard and Crouch, 1954):

1. The factor for correcting from directional intensity to integrated intensity is $2\pi/3$ for a $\cos^2\theta$ angular distribution.

2. The ratio of positive to negative muons in cosmic radiation is approximately 1·2 for various energies and is assumed to be true for slow muons also.

3. The fraction of negative muons which decay is 0·87. This is obtained from the known rates of interaction of slow muons with various constituents of air. The values for argon and nitrogen were obtained by interpolation of the experimental data.

4. The fraction of the negative muons which are captured by the argon in air saturated with water is 0·0081. This was calculated on the assumption that the capture rate is proportional to the square of the molecular diameter.

5. The fraction of the negative muons captured by argon which undergo nuclear reaction is 0·83.

For all altitudes from which precipitation can occur, the curve is exponential. We thus obtain

$$I(\mu^-) = 0{\cdot}000125 \exp(-x/247) \qquad (1)$$

for the number of nuclear reactions between slow negative muons and the argon in one gram of air per minute, where x is the atmospheric depth in gm cm $^{-2}$.

This expression can be integrated to obtain the total number of these interactions per minute which occur in a column of air one square metre in cross-section between an atmospheric depth x and sea-level (1030 gm cm^{-2}),

$$R(\mu^-) = 310\,[\exp(-x/247) - 0{\cdot}0154] \qquad (2)$$

The fraction of these interactions which result in the formation of chlorine-39, via the reaction

$$A^{40} + \mu^- = Cl^{39} + n + \nu \qquad (3)$$

where n is a neutron and ν a neutrino, has not been determined experimentally. but can be inferred from similar reactions with other elements. The neutron multiplicity for nuclear capture of negative muons has been determined for several elements (WIDGOFF, 1953). By interpolation of these results, a value of 0·7 is obtained for argon. This value can result from reactions in which neutrons are emitted as follows: 30% of the reactions involve the emission of no neutrons and 70% the emission of one neutron; or 40% (0), 50% (1), 10% (2); or 50% (0). 30% (1), 20% (2); etc. Reactions in which charged particles are emitted can be neglected (MORINAGA and FRY, 1953; WINSBERG, 1954a). Thus the maximum yield for chlorine-39 is 70%. A value of 50% is probably not much in error. The rate of production of chlorine-39 from slow muons is, therefore, approximately one-half that given by expression (2), or

$$R(Cl^{39}-\mu^-) = 155\,[\exp(-x/247) - 0{\cdot}0154] \qquad (4)$$

This is plotted in Fig. 1 versus the altitude in metres instead of the atmospheric depth. A graph of the height versus the atmospheric depth is given in Fig. 20 of ROSSI's paper (1948).

Chlorine-39 can also be formed by the interaction of other components of cosmic radiation with argon. The contribution from this source can be roughly estimated from the counting-rate of unshielded ionization chambers filled with argon and biased at 8 MeV, Fig. 9 of ROSSI (1948). (At this bias slow muons are not detected.) The exponential part of this curve, valid in the region of precipitation, can be expressed as

$$I(\text{i.c.}) = 0{\cdot}015 \exp(-x/138) \qquad (5)$$

for the counts per minute corresponding to the argon in one gram of air. Integration of (5) results in

$$R(\text{i.c.}) = 21{,}000 \exp[(-x/138) - 0{\cdot}000573], \qquad (6)$$

the total counts per minute for the argon in a column of air, one square metre in cross-section, between an atmospheric depth x and sea-level.

Since nearly all of these events are due to nuclear disintegrations, it is possible to estimate the rate of production of chlorine isotopes to be approximately 15 per cent from the prong-number distribution observed in an argon-filled cloud chamber (BROWN, 1954). The coefficient of expression (6) then becomes approximately 3000 per minute. The fraction of this rate which is associated with the formation of chlorine-39 can only be surmised from similar reactions induced by high-energy neutrons, protons, and X-rays on elements near argon in the periodic table.

(Marquez, 1952; Batzel *et al.*, 1951; Rudstam *et al.*, 1952; Rudstam, 1953; Belmont and Miller, 1954; Halperin *et al.*, 1955). It thus appears that chlorine-39 should comprise the order of 2–20% of all the chlorine isotopes which are formed by processes not involving slow muons. The final form for expression (6) thus becomes

$$R(\mathrm{Cl}^{39}\text{— i.c.}) = 60 \text{ to } 600\,[\exp(-x/138) - 0{\cdot}000573] \qquad (7)$$

which is plotted in Fig. 1 (versus height) for the two coefficents. The total rate of production of chlorine-39 is, therefore, the sum of (4) and (7).

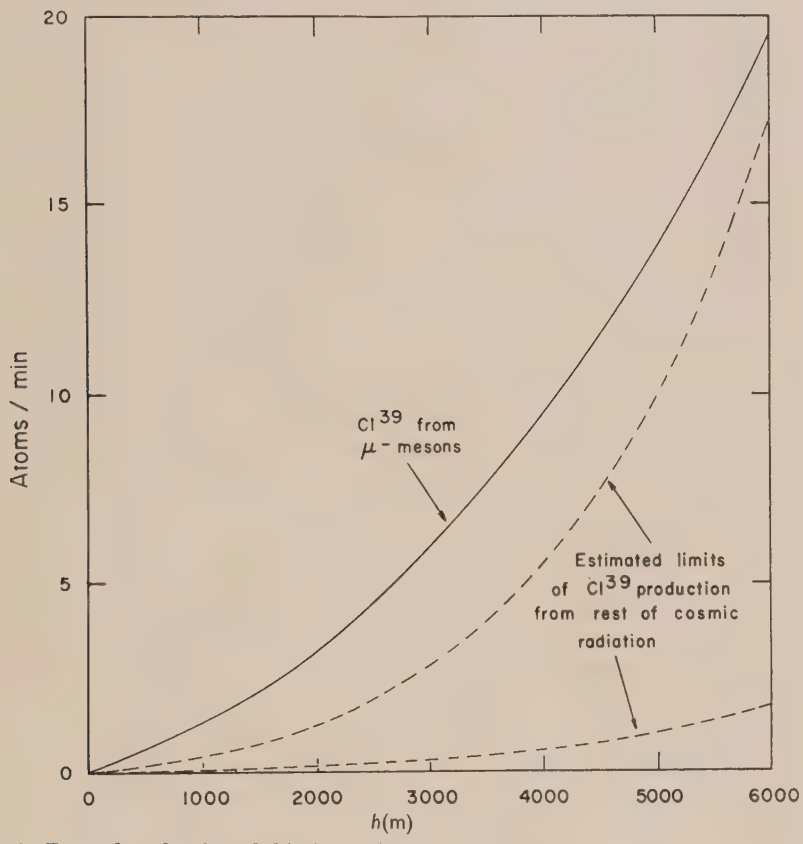

Fig. 1. Rate of production of chlorine-39 in a column of air one square metre in cross-section between sea-level and a height h.

In the lower atmosphere it appears that the production of chlorine-39 by slow negative muons is greater, perhaps by an order of magnitude, than the production by the other components of cosmic radiation, Fig. 1. This is consistent with the apparent absence of a half-hour component in experiments 1 and 5, Table 1, since the yields of chlorine-34 and -38 are expected to be smaller than that of chlorine-39 from slow negative muon reactions (Widgoff, 1953; Winsberg, 1954a), and greater from reactions involving other components of cosmic radiation (Brown, 1954; Marquez, 1952; Batzel *et al.*, 1951; Rudstam *et al.*, 1952; Rudstam, 1953; Belmont and Miller, 1954; Halperin *et al.*, 1955).

Several factors determine the fate of chlorine-39 after it has been formed: the motion of the air mass, the probability of decaying before removal from the air by precipitation, the altitude from which precipitation occurs, and the efficiency of extraction by rain, snow, and hail. Because of its relatively short half-life, the removal of chlorine-39 by other processes is undoubtedly negligible. The amount of chlorine-39 which is detected in any rain is the result of a combination of these factors. Hence, it is not surprising that only two of the rains listed in Table 1 contained an identifiable amount of chlorine-39.

Rain may originate from any altitude between the base and the top of a rain-cloud. Unfortunately, the measurements at the meteorological stations in the vicinity of Rehovoth give no indication of the top of the rain column at the place the samples were collected. Thus only a rough comparison can be made of the activity which was found with what might be expected. For a height of 5000 metres, which is perhaps representative, the chlorine-39 activity at saturation is approximately 15 to 24 disintegrations per minute per square metre (Fig. 1) or 6000 d.p.m. over an area of 300 square metres. This is approximately a factor of 10 greater than the 500 d.p.m. which were actually found in experiments 1 and 5, Table 1. The discrepancy is probably due to the small extraction efficiency of 5 ls of rain washing out approximately 1·5 million cubic metres of air.

The relatively small amount of chlorine-39 found in the other experiments may be due to the fact that the rain blew in, having washed the mass of air through which it was falling fairly clean of cosmic-ray induced activities by the time it reached the vicinity of the Weizmann Institute. This would account for the short time required to collect these samples (column 2 of Table 1) and for the smaller amount of chloride found (column 5). The especially low chloride content of experiment 3 is undoubtedly due to the additional fact that in this case the air mass, through which the rain fell, came from the east, where the atmospheric concentration of sodium chloride is low.

The work reported here is of a preliminary nature. However, it does show the feasibility of studying the phenomena involved by means of chlorine-39. In order to proceed satisfactorally in this direction, it is necessary to improve the procedure for collecting the samples, shorten the time till the beginning of counting, and devise a better means of counting the relatively large samples which are obtained. Several suggestions along this line are given elsewhere (WINSBERG, 1955). It would then be possible to study the extraction efficiency for chlorine-39 by measuring successive samples of water from a given rain and, in addition, improve the chances of detecting chlorine-34 and -38. Information concerning these isotopes of chlorine will help in understanding the nature of the cosmic-ray phenomena involved. In this connection, laboratory experiments on argon should be made with beams of negative muons (WINSBERG, 1954b) and other particles which are now available at various accelerators. The experimental determination of Fig. 1 in the manner described will provide further evidence on this point, since the shape of the production curve as a function of altitude depends on the component of cosmic radiation responsible for the formation of chlorine-39. For this purpose, accurate meteorological data are necessary.

The use of chlorine-39 as described here is potentially helpful in the study of

meteorological phenomena with particular application to rain. The relatively short half-life of this nuclide has the advantage of restricting the processes being studied to the vicinity and time of sample collection. In contrast, the processes pertaining to the other cosmic-ray-induced activities from the atmosphere, thus far detected, are worldwide in nature (Anderson *et al.*, 1947; Fireman, 1953; Kaufman and Libby, 1954; Arnold and Al-Salih, 1955).

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Data of rock analyses—II

Bibliography and index of rock analyses in the African periodical and serial literature.*

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Our problem is founded on the fact that on the one hand every man's reading time is limited, whilst on the other hand there must exist, somewhere among the millions of items of literature available, the particular ones which contain the ideas most apposite to his needs, if only there were some means of singling these out from the mass. J. E. HOLMSTROM

PART II comprises a bibliography of 247 references, taken from the African literature listed in Part I, in which new or previously unpublished chemical analyses of igneous and/or metamorphic rocks, meteorites, and natural glass appear, and two indexes, one by country and one by rock name, of these analyses. Analyses quoted from other publications, regardless of the place of publication, are not considered, and if an article contains only quoted analyses, it will not be found in the bibliography. Occasionally, a new analysis appears in two publications showing the same year of publication. In these instances, the decision has rested on such factors as the type of article, the amount of information given, or the availability of the publication.

For each reference there is given, in the following order, the name of the author, year of publication, title of the article, title of the journal, volume number, and pages. The title of each journal is abbreviated, but the full title can be found in Part I. Following the citation, brief notes indicate the countries represented, the total number of analyses for each country, and the rock types. The rock names are those used by the authors, but not all varieties have been listed. The various connotations given by individuals and the disparity in terminology between countries preclude here any attempt to standardize or interpret rock terms. One man's granite is another man's gneiss, and probably always will be. Because the African literature is essentially concerned with local areas within each country, only one country is represented in most of the references. Where rocks from border areas have been studied, or where, in making comparisons, new analyses from other localities have been introduced, two or more countries are represented. The selection of analyses of metamorphic rocks poses a problem in that it is impossible to draw a precise line between what is still considered a sedimentary rock and what is considered a metamorphic rock. The chances are that we have included too many rather than too few. As a rule, analyses of ores and highly altered rocks have been omitted.

In the geographic index, the references under each country are those that

* Publication authorized by the Director, U.S. Geological Survey.

contain analyses of rocks from localities within that country. The author's name and year of publication are given, and where an author has more than one publication in the same year, a small "a" and "b" are appended to the year. The number following each country is the total number of analyses for that country in the references listed. The number of analyses in each reference is given in the notes in the bibliography.

The rock name index follows the same style as the geographic index, giving the author's name and year. The rock names are those used by the authors. Attention is directed to several entries under the heading "Miscellaneous" and to four that are simply labelled "metamorphosed."

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Gigout, Marcel (1951) Études géologiques sur la méséta marocaine occidentale (arrière-pays de Casablanca, Mazagan et Safi): Morocco, Serv. Géol. Notes et Mém. **86,** 507 pp.; also published as Inst. Sci. Chérifien, Sér. Géol. Géog. Phys., Trav. 1 (originally no. 3). *Morocco:* 4; granite, granulite.

Glangeaud, Louis (1932) Étude géologique de la région littorale de la Province d'Alger: Algeria, Serv. Carte Géol. Bull., sér. 2, **8,** 627 pp. *Algeria:* 10; rhyolite, dellenite, dacitoid, granite, granodiorite, microgranite, quartz monzonite, quartz microgranodiorite.

Glangeaud, Louis and A. Aymé (1935) Notice détaillée de la carte géologique au 50,000 de l'Arba (Département d'Alger) et essai d'hydrologie de la Mitidja: Algeria, Serv. Carte Géol. Bull., sér. 2, **11,** 51 pp. *Algeria:* 1 dacitoid.

Glangeaud, Louis (1939) Les roches éruptives d'age secondaire et tertiaire, *in* Notice explicative des cartes géologiques au 500,000, Alger-Nord, Alger-Sud: Algeria, Serv. Carte Géol. Bull., 133–167. *Algeria:* 22; dolerite, granite, granodiorite, monzonite, rhyolite, dacite, dellenite, andesite, labradoritite, and others.

Glangeaud, Louis (1941) Roches éruptives et métamorphiques recueillies par M. Scaetta en Guinée Française et Côte d'Ivoire: Soc. Hist. Nat. Afr. Nord Bull. **32,** 183–190. *Fr. West Afr.:* 1 amphibolite.

Golding, Ernest (1932) Notes on the Wedza platinum mine, Southern Rhodesia: Chem. Met. Min. Soc. S. Afr. J. **33,** 192–195. *S. Rhodesia:* 2 platinum reef rock.

Golding, Ernest (1936) Chemical analyses of the rocks, ores, and minerals of Southern Rhodesia: S. Rhodesia Geol. Surv. Bull. **29,** 105 pp. *S. Rhodesia:* 39; various types.

Gorodiski, A. (1952) Notice explicative de la carte géologique du Sénégal au 20,000 (feuilles Ouakam et Dakar): Fr. West Afr. Dir. Mines, Bull. **10,** 5–57. *Fr. West Afr.:* 3 basanite.

Grantham, D. R., B. N. Temperley, and R. B. McConnell (1945) Explanation of the geology of degree sheet no. 17 (Kahama): Tanganyika Geol. Surv. Bull. **15,** 34 pp. *Tanganyika:* 3 granite.

Grosemans, P. (1935) Roches basiques de la région de Tenke: Com. Spéc. Katanga, Serv. Mines, Annales **5,** 8–13. *Belgian Congo:* 1 gabbro.

Grosemans, P. (1951) Intrusions basiques et laves des formations anciennes du Bas Congo: Musée Congo Belge, Sci. Géol. Annales, sér. 8°, **9,** 61 pp. *Belgian Congo:* 8; dolerite, diorite, phyllite, epidotite.

Gysin, Marcel (1937) Recherches géologiques et pétrographiques dans le Katanga méridional: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (4°), **6,** fasc. 1, 254 pp. *Belgian Congo:* 3; granite, gneiss, schist.

Hall, Arthur L. (1912) The geology of the Murchison Range and district: S. Afr. Geol. Surv. Mem. **6,** 184 pp. *S. Afr.:* 5; quartzite, schist.

Hall, Arthur L. (1920) Corundum in the northern and eastern Transvaal: S. Afr. Geol. Surv. Mem. **15,** 223 pp. *S. Afr.:* 2 pyroxenite.

Hall, Arthur L. (1923) On the marundites and allied corundum-bearing rocks in the Leydsdorp district of the eastern Transvaal: Geol. Soc. S. Afr. Tr. **25,** 43–67. *S. Afr.:* 7; marundite, plumasite.

Hall, Arthur L. and A. L. du Toit (1924) On the section across the floor of the Bushveld complex at the Hartebeestpoort dam, west of Pretoria: Geol. Soc. S. Afr. Tr. **26,** 69–97. *S. Afr.:* 3; norite, hybrid norite.

Hall, Arthur L. (1932) The Bushveld igneous complex of the central Transvaal: S. Afr. Geol. Surv. Mem. **28,** 554 pp. *S. Afr.:* 11; andesite, anorthosite, granite, syenite, bronzitite.

Hamilton, G. N. Gordon (1939) Further notes on the geology of the country around Kubuta (southern Swaziland): Geol. Soc. S. Afr. Tr. **41,** 199–203. *Swaziland:* 2 granite.

Haughton, S. H. and A. W. Rogers (1924) The volcanic rocks south of Zuurberg: Roy. Soc. S. Afr. Tr. **11,** pt. 3, 235–249. *S. Afr.:* 1 olivine basalt.

Haughton, S. H. and F. C. Partridge (1939) The meteorite fall of Macibini, Zululand: Geol. Soc. S. Afr. Tr. **41,** 205–210. *S. Afr.:* 1 meteorite.

Hirst, T. (1938) The geology of the Tarkwa goldfield and adjacent country: Gold Coast Geol. Surv. Bull. **10,** 24 pp. *Gold Coast:* 3 dike rock.

Hirst, T. (1942) The geology of the Konongo gold belt and surrounding country: Gold Coast Geol. Surv. Bull. **14,** 28 pp. *Gold Coast:* 1 granite.

Hitchen, C. S. (1937) Geological survey of No. 2 mining area, Kavirondo; Interim report and map of the north-east quadrant: Kenya Mines Geol. Dept. Rpt. **6,** 44 pp. *Kenya:* 3 felsite.

Holmes, Arthur (1937a) A contribution to the petrology of kimberlite and its inclusions: Geol. Soc. S. Afr. Tr. **39,** 379–427. *Uganda:* 1 katungite; *S. Afr.:* 1 melilitite; 10 inclusions of eclogite, biotite-appinite, granulite, chrome-diopside, saxonite, phlogopite-glimmerite, lherzolite, harzburgite.

Holmes, Arthur and H. F. Harwood (1937b) The petrology of the volcanic field of Bufumbira, south-west Uganda, and of other parts of the Birunga field: Uganda Geol. Surv. Mem. **3,** pt. 2, 300 pp. *Uganda:* 24; peridotite, banakite, pyroxenite, hypersthene latite, leucite basanite, olivine leucitite, katungite, kivite, murambite, absarokite, ugandite; *Belgian Congo:* 2; leucitite, murambite; *Canada:* 1 pyroxenite; *England:* 1 pyroxenite; *India:* 1 pyroxenite; *United States:* 1 pyroxenite.

Jamotte, A. (1934) Roches basiques et roches métamorphiques connexes de la région comprise entre la Lufunfu et la Mualaba; leurs relations avec les gisements de fer de la région: Com. Spéc. Katanga, Serv. Mines, Annales **4,** 22–55. *Belgian Congo:* 1 gabbro.

Janisch, Edna P. (1927) The occurrence of phosphates in the Zoutpansberg district of the northern Transvaal: Geol. Soc. S. Afr. Tr. **29,** 109–135. *S. Afr.:* 2; pegmatite, schist, and apatite.

Jansen, H. (1953) Observations on a dome-like structure north of Vereeniging, Transvaal: Geol. Soc. S. Afr. Tr. **56,** 45–58. *S. Afr.:* 5; gabbro, norite, diabase, diallage porphyry.

Jérémine, Elizabeth (1939) Roches éruptives et métamorphiques du Sahara occidental: Com. Études Hist. Sci. Afr. Occid. Franç. Pubs., sér. B, **5,** 1–52. *Fr. West Afr.:* 11; dolerite, granite, granodiorite, comendite, dacitoid; *Spanish Sahara:* 2; dolerite, gabbro.

Jérémine, Elizabeth (1942) Contribution à l'étude pétrographique des roches cristallines et métamorphiques de la Mauritanie: Fr. West Afr. Serv. Mines Bull. **6,** 99–140. *Fr. West Afr.:* 16; granite, diorite, plauenite, pyroxenite, granodiorite, gabbro, dolerite, rhyolite, gneiss.

Jérémine, Elizabeth (1948) Sur quelques roches provenant du Maroc oriental, aïounite et mestigmérite: Morocco, Serv. Géol. Notes et Mém. **71,** 67–71. *Morocco:* 1 fasinite.

Jérémine, Elizabeth (1950) Étude pétrographique des roches éruptives et métamorphiques du massif de Bou Agrao: Morocco, Serv. Géol. Notes et Mém. **74,** 119–147. *Morocco:* 13; syenite, plauenite, kersantite, monchiquite, monzonite, pyroxenite, cromaltite, nepheline akerite.

Junner, N. R. and H. F. Harwood (1928) Microscopical features and chemical analyses of certain representative igneous rocks from the Gold Coast, British West Africa: Gold Coast Geol. Surv. Bull. **4,** 16 pp. *Gold Coast:* 15; granite, diorite, keratophyre, nepheline syenite, gabbro, dolerite, metabasalt, basaltic tuff, peridotite, pyroxenite.

Junner, N. R. (1929) The petrology of the rocks of the Tarkwa-Abosso goldfield: Gold Coast Geol. Surv. Mem. **1,** 32–43. *Gold Coast:* 1 epidiorite.

Junner, N. R. (1930) Report of the Geological Department for the year 1929: Sierra Leone Geol. Surv. Rpt., 12 pp. *Sierra Leone:* 2; dunite, peridotite.

Junner, N. R. (1932a) The geology of the Obuasi goldfield: Gold Coast Geol. Surv. Mem. **2,** 43 pp. *Gold Coast:* 8; granite porphyry, norite, gabbro, phyllite, chlorite schist, dike.

Junner, N. R. (1932b) Report of the Director for the year 1931–1932: Gold Coast Geol. Surv. Rpt., 19 pp. *Gold Coast:* 2 schist.

Junner, N. R. (1933) Report of the Director for 1932–1933: Gold Coast Geol. Surv. Rept., 30 pp. *Gold Coast:* 2; volcanic glass, dike.

Junner, N. R. (1936) Report of the Director for 1935–1936: Gold Coast Geol. Surv. Rpt., 38 pp. *Gold Coast:* 6; granite, granodiorite, quartz diorite, albite porphyry, dolerite.

Junner, N. R. (1937) The geology of the Bosumtwi caldera and surrounding country: Gold Coast Geol. Surv. Bull. **8,** 1–38. *Gold Coast:* 3; lava, tuff, dike.

Junner, N. R. (1940) Geology of the Gold Coast and western Togoland: Gold Coast Geol. Surv. Bull. **11,** 40 pp. *Gold Coast:* 4; dolerite, basalt, granodiorite; *Togoland:* 1 dolerite.

Junner, N. R. (1943) The diamond deposits of the Gold Coast: Gold Coast Geol. Surv. Bull. **12,** 52 pp. *Gold Coast:* 2; phyllite, calc-chlorite-schist rock.

Junner, N. R. and W. T. James (1947) Chemical analyses of Gold Coast rocks, ores and minerals: Gold Coast Geol. Surv. Bull. **15,** 66 pp. *Gold Coast:* 13; granite, aplite, dolerite, marble, phyllite, hornstone, schist, amphibolite.

Keep, F. E. (1929) The geology of the Shabani mineral belt, Belingwe district: S. Rhodesia Geol. Surv. Bull. **12,** 179 pp. *S. Rhodesia:* 12; serpentine, dunite, greenstone, granite, carbonate rocks.

Keep, F. E. (1930) The geology of the chromite and asbestos deposits of the Umvukwe Range, Lomagundi and Mazoe districts: S. Rhodesia Geol. Surv. Bull. **16,** 105 pp. *S. Rhodesia:* 4; granite, serpentine, websterite.

Kent, Leslie E. and J. J. Frankel (1949) Studies on Karroo dolerites. 4. On intrusions of glass in dolerite: Geol. Soc. S. Afr. Tr. **51,** 179–193. *S. Afr.:* 5 glass.

King, Basil C. (1939) Appendix to petrology of some Uganda granites: Uganda Geol. Surv. Bull. **3,** 136–139. *Uganda:* 9 granite.

King, Basil C. and A. M. J. De Swardt (1949a) The geology of the Osi area, Ilorin Province: Nigeria Geol. Surv. Bull. **20,** 92 pp. *Nigeria:* 10; granite, gneiss, norite, metagabbro.

King, Basil C. (1949b) The Napak area of southern Karamoja, Uganda: Uganda Geol. Surv. Mem. **5,** 57 pp. *Uganda:* 13; andesite, phonolite, trachyte, carbonatite, nephelinite.

Kouriatchy, N. (1933) Contribution à la connaissance de la géologie du Territoire du Togo: Com. Études Hist. Sci. Afr. Occid. Franç. Bull. **16,** no. 4, 493–629. *Fr. Togo:* 11; granite, granodiorite, quartz diorite, gabbro, quartz norite, eclogite, serpentine, amphibolite.

Lacroix, Alfred (1925) Sur une chute de météorite survenue dans la Haute-Volta, en 1924: Com. Études Hist. Sci. Afr. Occid. Franç. Bull. **8,** no. 4, 529–531. *Fr. West Afr.:* 1 meteorite.

Lacroix, Alfred (1926) Note sur quelques roches grenues de l'Afrique Occidentale Française: Com. Études Hist. Sci. Afr. Occid. Franç. Bull. **9,** no. 1, 38–51. *Fr. West Afr.:* 9; granite, monzonite, granodiorite, syenite.

Lacroix, Alfred (1941) Les gisements de phlogopite de Madagascar et les pyroxénites qui les renferment: Madagascar, Serv. Mines, Annales Géol. **11,** 119 pp. *Madagascar:* 60; pyroxenite, plagioclase rock, garnet rock, scapolite rock, epidote rock, sakenite, pegmatite, dissogénite, amphibolite, dunite, sagvandite, lamboandite, idocrasite, aplite, corundum rock, and others.

Latsky, Rudolph (1943) The magmatic copper ores of Namaqualand: Geol. Soc. S. Afr. Tr. **45,** 109–150. *S. Afr.:* 9; anorthosite, gabbro, diorite, norite, pyroxenite, hypersthenite, biotite-magnetite rock.

Legoux, Pierre (1939) Le massif de Man (Côte d'Ivoire), essai de géologie pétrographique: Fr. West Afr. Serv. Mines, Bull. **3,** 94 pp. *Fr. West Afr.:* 18; granite, norite, gabbro, hypersthenite, plagioclase rock, pyroxenite, quartzite.

Lelubre, Maurice (1952) Recherches sur la géologie de l'Ahaggar central et occidental (Sahara Central): Algeria, Serv. Carte Géol. Bull. sér. 2, **22** (t. 1, 354 pp., t. 2, 385 pp.). *Algeria:* 26; granite, rhyolite, trachyte, gneiss.

Lightfoot, Ben (1927) Traverses along the Great Dyke of S. Rhodesia: S. Rhodesia Geol. Surv. Short Rpt. **21,** 8 pp. *S. Rhodesia:* 5; serpentine, norite, harzburgite, websterite, platinum reef.

Lightfoot, Ben and R. Tyndale-Biscoe (1931) The geology of the country west of Mt. Darwin: S. Rhodesia Geol. Surv. Bull. **10,** 54 pp. *S. Rhodesia:* 4; adamellite, granodiorite, felsite, quartz porphyry.

Lightfoot, Ben (1939) Notes on the south-eastern part of Southern Rhodesia: Geol. Soc. S. Afr. Tr. **41,** 193–198. *S. Rhodesia:* 5; rhyolite, basalt, granophyre, gabbro.

Lightfoot, Ben (1941) The Great Dyke of Southern Rhodesia: Geol. Soc. S. Afr. Proc. **43,** xxvi–xlv. *S. Rhodesia:* 6; pyroxenite, enstatite rock.

Lombaard, B. V. (1930) The geology of a centrocline, 18 miles north-east of Pretoria: Geol. Soc. S. Afr. Tr. **32,** 151–164. *S. Afr.:* 1 diabase.

Lombaard, B. V. (1931) The geology of the north-eastern Pretoria district and adjoining country: S. Afr. Geol. Surv., Map Sheet Expl., Sheet no. 18 (Moos River), 43 pp. *S. Afr.:* 1 andesitic felsite.

Lombaard, B. V. (1933) The felsites and their relations in the Bushveld complex: Geol. Soc. S. Afr. Tr. **35,** 125–190. *S. Afr.:* 19; granite, granophyre, felsite, syenite, quartz gabbro, norite.

Lombaard, B. V. (1934) Discussion of "Breccias and associated rocks occurring north-east of Pretoria" by F. A. Venter: Geol. Soc. S. Afr. Tr. **36,** 61–63. *S. Afr.:* 1 trachyte.

Lombaard, B. V. (1935) On the differentiation and relationships of the rocks of the Bushveld complex: Geol. Soc. S. Afr. Tr. **37,** 5–52. *S. Afr.:* 15; granite, pyroxenite, felsite, granophyre, diabase, norite.

Lombaard, B. V. (1940) Dykes in the Transvaal: Geol. Soc. S. Afr. Proc. **42,** xxvii–xlii. *S. Afr.:* 17; granodiorite, quartz diorite, dolerite, syenite, foyaite, diabase.

Lombaard, B. V. (1952) Karroo dolerites and lavas: Geol. Soc. S. Afr. Tr. **55,** 175–198. *S. Afr.:* 16; dolerite, basalt, limburgite, rhyolite, granophyre, microgranite.

Macgregor, A. M. (1927) The problem of the Precambrian atmosphere: S. Afr. J. Sci. **24,** 155–172. *S. Rhodesia:* 1 spilite.

Macgregor, A. M. (1928) The geology of the country around the Lonely mine, Bubi district: S. Rhodesia Geol. Surv. Bull. **11,** 96 pp. *S. Rhodesia:* 1 greenstone.

Macgregor, A. M. (1930) The geology of the country between Gatooma and Battlefields: S. Rhodesia Geol. Surv. Bull. **17,** 144 pp. *S. Rhodesia:* 9; granite, syenite, porphyry, serpentine, tuff.

Macgregor, A. M. (1932) The geology of the country around Que Que, Gwelo district: S. Rhodesia Geol. Surv. Bull. **20,** 113 pp. *S. Rhodesia:* 3 granite.

Macgregor, A. M. (1935) The geology of the Makaha gold belt, Mtoko district: S. Rhodesia Geol. Surv. Bull. **28,** 47 pp. *S. Rhodesia:* 1 pillow lava.

Macgregor, A. M. (1937) The geology of the country around Hunters Road, Gwelo district: S. Rhodesia Geol. Surv. Bull. **31,** 78 pp. *S. Rhodesia:* 6; greenstone, andesite, pillow lava, serpentine, granite.

Mathias, Morna (1940) The occurrence of barite in an iron ore deposit in Namaqualand: Roy. Soc. S. Afr. Tr. **28,** pt. 3, 207–217. *S. Afr.:* 1 magnetite-barite rock.

Mathias, Morna (1941) A comparative study of the Namaqualand granites: Geol. Soc. S. Afr. Tr. **43,** 175–203. *S. Afr.:* 6; granite, gneiss.

Maufe, H. B. (1928) On the formation of red soil and black vlei soil from dolerite at Salisbury, Southern Rhodesia: S. Afr. J. Sci. **25,** 156–167. *S. Rhodesia:* 1 dolerite.

McLachlan, Geoffrey R. (1950) The geology of Dassen Island: Geol. Soc. S. Afr. Tr. **52,** 377–384. *S. Afr.:* 2; granite, xenolith.

Meunier, Stanislaus (1913) Étude chimique, minéralogique, lithologique et cosmique de la météorite d'el Nakhla el Baharia: Inst. Égyptien Mém. **6,** fasc. 5, 257–283. *Egypt:* 1 meteorite.

Meyer, André (1953) Le Volcan Nyamuragira et son éruption de 1951–1952: Inst. Roy. Col. Belge, Bull. Séances **24,** 233–286. *Belgian Congo:* 7 basanite.

Michot, Paul (1938) Étude pétrographique et géologique du Ruwenzori septentrional: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (8°) **8,** fasc. 1, 272 pp. *Belgian Congo:* 19; granite, alaskite, gneiss, syenite, dolerite, gabbro, hornblendite, amphibolite, xenolith.

Morgan, S. C. (1929) The geology of the Gaika gold mine, Que Que, S. Rhodesia: S. Rhodesia Geol. Surv. Bull. **14,** 42 pp. *S. Rhodesia:* 4; aplite, serpentine, magnesite rock, schist.

Mountain, Edgar D. (1935) The Bowden meteoric stone: Albany Mus. Rec. **4,** pt. 2, 248–253. *S. Afr.:* 1 meteorite.

Mountain, Edgar D. (1944) The dikes of the Transkei Gaps: Geol. Soc. S. Afr. Tr. **46,** 55–74. *S. Afr.:* 5; dolerite, quartzite.

Mountain, Edgar D. (1945) Further examples of syntexis by Karroo dolerite: Geol. Soc. S. Afr. Tr. **47,** 107–122. *S. Afr.:* 4 metamorphosed sediments.

Nel, Hans J. (1941) The basal rocks of the Bushveld igneous complex, north of Pretoria: Geol. Soc. S. Afr. Tr. **43,** 37–68. *S. Afr.:* 3; diabase, gabbro.

Nel, Louis T. (1935) The geology of the Klerksdorp-Ventersdorp area: S. Afr. Geol. Surv. Spec. Pub., 159 pp. *S. Afr.:* 6 lava.

Nell, G. and W. C. Brink (1944) The petrology of the Western Province dolerites: Univ. Stellenbosch Annals **22,** sec. A, 27–62. *S. Afr.:* 9 dolerite.

Oates, Frank (1934) Ultrabasic nickel-bearing rock: Tanganyika Geol. Surv. Ann. Rpt. 1933, 30–31. *Tanganyika:* 1 peridotite.

Obermuller, Alphonse (1941) Description pétrographique et étude géologique de la région forestière de la Guinée Française: Fr. West Afr. Serv. Mines **5,** 207 pp. *Fr. West Afr.:* 25; granite, gneiss, quartzite, amphibolite, pyroxenite, lherzolite.

Phaup, A. E. (1932) The geology of the Antelope gold belt: S. Rhodesia Geol. Surv. Bull. **21,** 119 pp. *S. Rhodesia:* 7; tonalite, basalt, amphibolite, serpentine, schist.

Phaup, A. E. (1933) The geology of the Lower Gwanda gold belt: S. Rhodesia Geol. Surv. Bull. **24,** 74 pp. *S. Rhodesia:* 1 granite.

Phaup, A. E. (1937) The geology of the Umtali gold belt: S. Rhodesia Geol. Surv. Bull. **32,** 181 pp. *S. Rhodesia:* 6; adamellite, dolerite, quartz porphyry, greenstone, serpentine.

Phaup, A. E. and F. O. S. Dobell (1938) The geology of the Lower Umfuli gold belt, Hartley and Lomagundi districts: S. Rhodesia Geol. Surv. Bull. **34,** 143 pp. *S. Rhodesia:* 5; greenstone, schist, granodiorite, pegmatite, quartz porphyry.

Poldervaart, Arie (1944) The petrology of the Elephant's Head dike and the New Amalfi sheet (Matatiele): Roy. Soc. S. Afr. Tr. **30,** pt. 2, 85–119. *S. Afr.:* 13; tholeiite, picrite, dolerite, granophyre, xenolith, metamorphosed grit.

Poldervaart, Arie (1948) The petrology of the Mount Arthur dolerite complex, East Griqualand: Roy. Soc. S. Afr. Tr. **31,** 83–110. *S. Afr.:* 12; tholeiite, dolerite, basalt.

Poldervaart, Arie and Johan W. Von Backström (1950) A study of an area at Kakamas (Cape Province): Geol. Soc. S. Afr. Tr. **52,** 433–495. *S. Afr.:* 17; adamellite, gneiss, granulite, norite, metagabbro, amphibolite, schist, dike.

Polinard, Edmond (1934) Le socle ancien inférieur à la série schisto-calcaire du Bas-Congo: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (4°) **2,** fasc. 4, 99 pp. *Belgian Congo:* 7 gneiss.

Polinard, Edmond (1935a) Contribution à l'étude des roches éruptives et des schistes cristallins de la région de Bondo: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (4°) **4,** fasc. 2, 41 pp. *Belgian Congo:* 10; granite, gneiss, gabbro, amphibolite.

Polinard, Edmond (1935b) Constitution géologique et pétrographique des bassins de la Kotte et du M'Bari dans la région de Bria-Yalinga (Oubangui-Chari): Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (4°) **4,** fasc. 3, 134 pp. *Fr. Equat. Afr.:* 32; granite, gneiss, aplite, pegmatite, granitoid rock, amphibolite, migmatite, schist, quartzite.

Polinard, Edmond (1939a) La bordure nord du socle granitique dans la région de la Lubi et de la Bushimai (Congo Belge): Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (8°) **9,** fasc. 1, 48 pp. *Belgian Congo:* 12; granite, granodiorite, dolerite, amphibolite.

Polinard, Edmond (1939b) Les roches alcalines de Chianga (Angola) et les tufs associés: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (8°) **9,** fasc. 4, 27 pp. *Angola:* 4; granite, phonolite, trachyte, nepheline syenite.

Polinard, Edmond (1941) Het doleriet van den samenloop Sankuru-Bushimai: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (8°) **10,** fasc. 4, 31 pp. *Belgian Congo:* 2 dolerite.

Polinard, Edmond (1944a) Étude pétrographique de l'entre-Lulua-Lubilash du parallèle 7° 30′ S. à la frontière de l'Angola: Inst. Roy. Col. Belge, Sec. Sci. Nat. Méd. Mém. (4°) **7,** fasc. 1, 120 pp. *Belgian Congo:* 53; granite, granodiorite, pegmatite, norite, dolerite, gabbro, gneiss, amphibolite.

Polinard, Edmond (1944b) La plagioclasolite quartzique aurifère de la Katongo (Bassin de la Lulua, Congo Belge): Inst. Roy. Col. Belge, Bull. Séances **15,** 102–118. *Belgian Congo:* 3 quartz norite.

Pollett, J. D. (1932) Report, *in* Geological section of the Geological and Mines Department report for the period January 1930 to June 1931: Sierra Leone Geol. Surv. Rpt. 1930 and 1931, 7–14. *Sierra Leone:* 1 granite.

Potgieter, C. T. (1950) The structure and petrology of the George granite plutons and the invaded pre-Cape sedimentary rocks: Univ. Stellenbosch Annals **26,** sec. A, 323–412. *S. Afr.:* 22; granite, dolerite, schist.

Pulfrey, William (1946a) Geological survey of Maragoli, northern Kavirondo (with map): Kenya Mines Geol. Dept. Rpt. **9,** 54 pp. *Kenya:* 1 adamellite.

Pulfrey, William (1946b) The nature and origin of a soapstone from near Kisii: East Afr. Nat. Hist. Soc. J. **19,** 1–11. *Kenya:* 3 soapstone.

Raeburn, C. (1927) Tinstone in the Calabar district: Nigeria Geol. Surv. Bull. **11,** 72–88. *Nigeria:* 2 metamorphic garnet rock.

Ranoux, Jacques (1952) Étude géologique de Djebel Bechtout: Algeria, Serv. Carte Géol. Bull., sér. 2, Trav. Récents Collab. **3,** 177–188. *Algeria:* 1 granite.

Roberts, R. O. (1947) Meteorites in Uganda: Uganda J. **11,** 42–46. *Uganda:* 1 meteorite.

Roche, Hubert, de la (1953) Étude de la province aurifère de Manajary: Madagascar Bur. Géol. Trav. **49,** 94 pp. *Madagascar:* 2; granite, quartz oligoclase rock.

Rogers, A. W. (1917) The nature of the copper deposits of Little Namaqualand: Geol. Soc. S. Afr. Proc. 1916, xxi–xxxiv. *S. Afr.:* 2; diorite, norite.

Rogers, A. W. (1922) The geology of the country around Heidelberg: S. Afr. Geol. Surv. Spec. Pub., 80 pp. *S. Afr.:* 6; norite, quartz keratophyre, sölvsbergite, pyroxenite.

Rogers, A. W. (1926) Notes on the north-eastern part of the Zoutpansberg district: Geol. Soc. S. Afr. Tr. **28,** 33–53. *S. Afr.:* 2; lava, basalt.

Rogers, A. W. (1935) The "solid" geology of the Kalahari: Roy. Soc. S. Afr. Tr. **23,** pt. 2, 165–176. *Bechuanaland:* 1 porphyry.

Roubault, Marcel (1934) La Kabylie de Collo, étude géologique: Algeria, Serv. Carte Géol. Bull. sér. 2, **10,** 272 pp. *Algeria:* 68; granite, granodiorite, aplite, rhyolite, kentallenite, monzonite, gabbro, lherzolite, amphibolite, gneiss, schist, hornfels, granulite, metamorphosed rock.

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Royer, Louis (1933) Étude pétrographique des roches métamorphiques du massif d'Alger: Algeria, Serv. Carte Géol. Bull. sér. 2, Trav. Récents Collab. **2,** 33–55. *Algeria:* 3; gneiss, schist.

Saggerson, E. P. (1952) Geology of the Kisumu district: Kenya Geol. Surv. Rpt. **21,** 86 pp. *Kenya:* 19; granite, syenite, ijolite, nephelinite, carbonatite, phonolite, andesite tuff.

Scholtz, Douglas L. (1937) The magmatic nickeliferous deposits of East Griqualand and Pondoland: Geol. Soc. S. Afr. Tr. **39,** 81–120. *S. Afr.:* 8; hyperite, picrite, troctolite, monzonite, microgranite, gabbro.

Scholtz, Douglas L. (1947) On the younger pre-Cambrian granite plutons of the Cape Province: Geol. Soc. S. Afr. Proc. **49,** xxxv–lxxxii. *S. Afr.:* 35; granite, phyllite, quartzite, felsite.

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Shand, S. James (1922b) The igneous complex of Leeuwfontein, Pretoria district: Geol. Soc. S. Afr. Tr. **24,** 232–249. *S. Afr.:* 2; trachyte, syenite.

Shand, S. James (1923) The alkaline rocks of the Franspoort line, Pretoria district: Geol. Soc. S. Afr. Tr. **25,** 81–100. *S. Afr.:* 3; foyaite, phonolite.

Shand, S. James (1929) The geology of Pilansberg (Pilaan's Berg) in the western Transvaal; a study of alkaline rocks and ring-intrusions: Geol. Soc. S. Afr. Tr. **31,** 97–156. *S. Afr.:* 3; foyaite, syenite.

Shand, S. James (1932) The granite-syenite-limestone complex of Palabora, eastern Transvaal, and the associated apatite deposits: Geol. Soc. S. Afr. Tr. **34,** 81–105. *S. Afr.:* 2; granite, syenite.

Shukri, N. M. (1945) On the geology of the Brothers Islets, northern Red Sea: Fouad I Univ. Fac. Sci. Bull. **25,** 173–196. *Egypt:* 2 gabbro.

Simmons, W. C. (1932) Laboratory work: Uganda Geol. Surv. Ann. Rpt. for the year ended 31 Dec. 1931, 16. *Uganda:* 1 tonalite.

Simmons, W. C., and H. F. Harwood (1935) Petrology of the Kilembe copper deposits: Uganda Geol. Surv. Bull. **2,** 13–27. *Uganda:* 3; granulite, pegmatite.

Smith, W. Campbell and Max H. Hey (1952) The silica-glass from the crater of Aouelloul (Adrar, western Sahara): Inst. Franç. Afr. Noire Bull. **14,** no. 3, 762–776. *Fr. West Afr.:* 2 silica glass.

Söhnge, P. G. (1945) The geology of the Messina copper mines and surrounding country: S. Afr. Geol. Surv. Mem. **40,** 272 pp. *S. Afr.:* 5; amphibolite, gneiss, schist, granite, garnet-magnetite rock.

Söhnge, P. G. and John de Villiers (1949) The Kuboos pluton and its associated line of intrusives: Geol. Soc. S. Afr. Tr. **51,** 1–36. *S. Afr.:* 1 granite.

Sorotchinsky, C. (1952) Étude des albitites et de quelques roches carbonatées du Bassin de la Kadubu (Kivu): Musée Congo Belge, Sci. Géol. Annales, sér. 8°, **10,** 83–117. *Belgian Congo:* 17 albitite.

Stagman, J. G. (1953) The geology of the country between Concession and Msonneddi (Mazoe district): S. Rhodesia Geol. Surv. Bull. **41,** 48 pp. *S. Rhodesia:* 4; granulite, granite, corundum-rich rocks.

Stockley, G. M. and G. J. Williams (1938) Explanation of the geology, degree sheet no. 1 (Karagwe tinfields): Tanganyika Geol. Surv. Bull. **10,** 91 pp. *Tanganyika:* 2 granite.

Stockley, G. M. (1947) Report on the geology of Basutoland: Basutoland Govt. Geologist Rpt., 114 pp. *Basutoland:* 2 basalt.

Stockley, G. M. (1948) Geology of north, west, and central Njombe district, Southern Highlands Province: Tanganyika Geol. Surv. Bull. **18,** 67 pp. *Tanganyika:* 9; serpentine, norite, gabbro, anorthosite, syenogranite.

Strauss, C. A. and F. C. Truter (1945) The Bushveld granites in the Zaaiplaats tin mining area: Geol. Soc. S. Afr. Tr. **47,** 47–77. *S. Afr.:* 6 granite.

Strauss, C. A. (1948a) The petrology of a small dolerite and granophyre complex in the New Belgium Block, Potgietersrust district: Geol. Soc. S. Afr. Tr. **50,** 73–104. *S. Afr.:* 10; dolerite, tonalite, granophyre.

Strauss, C. A. (1948b) Granitisation and rheomorphism associated with the Bushveld granite near the Leeuwpoort tin mine: Geol. Soc. S. Afr. Tr. **50,** 161–170. *S. Afr.:* 5; quartzite, leptite.

Strauss, C. A. and F. C. Truter (1951a) The alkali complex at Spitskop, Sekukuniland, eastern Transvaal: Geol. Soc. S. Afr. Tr. **53,** 81–125. *S. Afr.:* 27; carbonatite, granite, syenite, foyaite, granophyre, umptekite, ijolite, basalt, diorite, theralite, dolerite, lestiwarite.

STRAUSS, C. A. and F. C. TRUTER (1951b) Post-Bushveld ultrabasic, alkali, and carbonatitic eruptives at Magnet Heights, Sekukuniland, eastern Transvaal: Geol. Soc. S. Afr. Tr. **53,** 169–190. *S. Afr.:* 5; carbonatite, albitite, picrite, pleonaste, prehnite-aegirine rock.

SWIFT, W. H., W. C. WHITE, J. W. WILES, and B. G. WORST (1953) The geology of the Lower Sabi coalfield: S. Rhodesia Geol. Surv. Bull. **40,** 96 pp. *S. Rhodesia:* 17; granulite, gneiss, eclogite, perknite, dolerite, granophyre, basalt, ijolite, nephelinite, andesite.

TALJAARD, M. S. (1937) South African melilite basalts and their relations: Geol. Soc. S. Afr. Tr. **39,** 281–316. *S. Afr.:* 4 basalt.

TAZIEFF, HAROUN (1951) L'éruption du Volcan Gituro (Kivu, Congo Belge) de mars à juillet 1948: Belgian Congo and Ruanda-Urundi Serv. Géol. Mém. **1,** 158 pp. *Belgian Congo:* 4 kivite.

TEALE, E. O. (1932) Geological Survey annual report, 1931: Tanganyika Geol. Surv. Ann. Rpt. 1931, 49 pp. *Tanganyika:* 1 syenite.

TEMPERLEY, B. N. (1938) The geology of the country around Mpwapwa: Tanganyika Geol. Surv. Short Paper **19,** 58 pp. *Tanganyika:* 1 granodiorite.

TERMIER, HENRI (1936) Études géologiques sur le Maroc central et le Moyen Atlas septentrional: Morocco, Serv. Géol. Notes et Mém. **33,** t. 3, 1087–1566. *Morocco:* 14; dacitoid, basalt, dolerite, phonolite, murite, tahitite, ankaratrite, fasinite.

TERMIER, HENRI, BORIS OWODENKO, and JULES AGARD (1950) Les gîtes d'étain et de tungstène de la région d'Oulmès (Maroc central): Morocco, Serv. Géol. Notes et Mém. **82,** 328 pp. *Morocco:* 36; granite, schist.

THIÉBAUT, JEAN (1951) Étude géologique des terrains métamorphiques de la Grand Kabylie: Algeria, Serv. Carte Géol. Bull. sér. 5, **6,** 175 pp. *Algeria:* 19; granite, pegmatite, gneiss, amphibolite, schist, epidiorite, diallagite, metamorphic limestone, transition rocks.

TORRANCE, WILLIAM (1923) The disaggregation of some rock and soil-forming minerals: S. Afr. J. Sci. **20,** 241–255. *S. Afr.:* 3; granite, dolerite.

TORRANCE, WILLIAM (1924) Some metamorphic mudstones: S. Afr. J. Sci. **21,** 182–188. *S. Afr.:* 2 hornfels.

TYNDALE-BISCOE, R. (1931) The geology of the country around Shamva, Mazoe district: S. Rhodesia Geol. Surv. Bull. **18,** 87 pp. *S. Rhodesia:* 4; tonalite, porphyry, epidiorite.

TYNDALE-BISCOE, R. (1932) Interim report on the geology of part of the Salisbury gold belt: S. Rhodesia Geol. Surv. Bull. **19,** 39 pp. *S. Rhodesia:* 2 lepidolite rock.

TYNDALE-BISCOE, R. (1933) The geology of the central part of the Mazoe Valley gold belt: S. Rhodesia Geol. Surv. Bull. **22,** 120 pp. *S. Rhodesia:* 14; granite, quartz porphyry, diorite, epidiorite, rhyolite, biotite schist.

TYNDALE-BISCOE, R. (1939) Notes on a monzonitic complex and associated rocks in the Gwanda district, Southern Rhodesia: Geol. Soc. S. Afr. Tr. **41,** 83–102. *S. Rhodesia:* 6; adamellite, monzonite, granite.

TYNDALE-BISCOE, R. (1940) The geology of the country around Gwanda: S. Rhodesia Geol. Surv. Bull. **36,** 200 pp. *S. Rhodesia:* 4; granite, gneiss, rhyolite.

TYNDALE-BISCOE, R. (1949) The geology of the country around Gwelo: S. Rhodesia Geol. Surv. Bull. **39,** 145 pp. *S. Rhodesia:* 6; hornfels, serpentine, talc-carbonate schist, limburgite, granite.

VAN BILJON, S. (1940) The Kuboos batholith, Namaqualand, South Africa: Geol. Soc. S. Afr. Tr. **42,** 123–219. *S. Afr.:* 18; granite, syenite, kersantite, camptonite, bostonite, spessartite, dike rock.

VAN BILJON, S. (1950) The transformation of the upper part of the Pretoria Series in the Bushveld igneous complex: Geol. Soc. S. Afr. Tr. **52,** 1–197. *S. Afr.:* 39; quartzite, "chert," felsite, granophyre, granulite, hornfels, anorthosite, foyaite, diorite, norite, pyroxenite, gabbro, diopside rock.

VAN DER MERWE, A. J. (1946) Note on the determination of minute quantities of chromium in igneous rocks: Geol. Soc. S. Afr. Tr. **48,** 15–16. *S. Afr.:* 1 basalt.

VAN EEDEN, O. R., F. C. PARTRIDGE, L. E. KENT, and J. W. BRANDT (1939) The mineral deposits of the Murchison Range, east of Leydsdorp: S. Afr. Geol. Surv. Mem. **36,** 163 pp. *S. Afr.:* 1 biotite schist.

Van Rooyen, D. P. (1951) The metamorphic rocks constituting the floor of the Bushveld igneous complex, north of Potgietersrust: Geol. Soc. S. Afr. Tr. **53,** 65–71. *S. Afr.:* 3; leptite, pseudogranophyre.

Van Zijl, P. J. (1950) The complex dioritic stocks west of the Malmesbury-Paardeberg granite pluton: Univ. Stellenbosch Annals **26,** sec. A, 481–507. *S. Afr.:* 13; gabbro, diorite, dike rock.

Van Zyl, J. S. (1950) Aspects of the geology of the northern Soutpansberg area: Univ. Stellenbosch Annals **26,** sec. A, 1–95. *S. Afr.:* 7; basalt, diorite, anorthosite, hornblendite.

Verhoogen, Jean (1940) Les pipes de kimberlite du Katanga: Com. Spéc. Katanga, Serv. Mines Annales **9,** 3–49. *Belgian Congo:* 1 kimberlite.

Verhoogen, Jean (1948) Les éruptions 1938–1940 du Volcan Nyamuragira: Inst. Parcs Nat. Congo Belge, Expl. Parc Nat. Albert, Missions J. Verhoogen (1938 et 1940) **1,** 186 pp. *Belgian Congo:* 3 lava.

Versfeld, W. (1915) The geological structure of portions of German South-West Africa: S. Afr. J. Sci. **11,** 187–238. *S. West Afr.:* 2; diorite, metasyenite.

Visser, D. J. L. (1948) Acid lavas from the neighbourhood of Lekkerwater Siding, South-West Africa: Geol. Soc. S. Afr. Tr. **50,** 171–176. *S. West Afr.:* 1 porphyry.

Von Backström, J. W. (1952) The Dominion Reef and Witwatersrand systems between Wolmaranstad and Ottosdal, Transvaal: Geol. Soc. S. Afr. Tr. **55,** 53–71. S. *Afr.:* 10; andesite, rhyolite, quartz porphyry, hyperite, xenolith, contact rock.

Wade, F. B. and F. Oates (1938) An explanation of degree sheet no. 52 (Dodoma): Tanganyika Geol. Surv. Short Paper **17,** 58 pp. *Tanganyika:* 3; adamellite, aplosyenite, granite.

Wagner, Percy A. (1921) The Mutue Fides-Stavoren tinfields: S. Afr. Geol. Surv. Mem. **16,** 192 pp. *S. Afr.:* 5; granite, granophyre, aplite.

Wagner, Percy A. (1922) The Pretoria Salt-pan, a soda caldera: S. Afr. Geol. Surv. Mem. **20,** 136 pp. *S. Afr.:* 1 granite.

Wagner, Percy A. (1923a) The chromite of the Bushveld igneous complex: S. Afr. J. Sci. **20,** 223–235. *S. Afr.:* 3 chromitite.

Wagner, Percy A. (1923b) A remarkable rock from the Pretoria Salt-pan: Geol. Soc. S. Afr. Tr. **25,** 101–106. *S. Afr.:* 1 porphyry.

Wagner, Percy A. (1924) Magmatic nickel deposits of the Bushveld complex in the Rustenburg district, Transvaal: S. Afr. Geol. Surv. Mem. **21,** 181 pp. *S. Afr.:* 8; granite, anorthosite, norite, bronzitite, harzburgite, serpentine.

Wagner, Percy A. (1925) The platinum deposits in the western part of the Lydenburg district, Transvaal: S. Afr. J. Ind. **8,** no. 2, 90–113. *S. Afr.:* 2; dunite, norite.

Wagner, Percy A. (1926) Notes on the platinum deposits of the Bushveld igneous complex: Geol. Soc. S. Afr. Tr. **28,** 83–133. *S. Afr.:* 2 norite.

Wagner, Percy A. (1927a) The geology of the north-eastern part of the Springbok Flats and surrounding country: S. Afr. Geol. Surv. Map Sheet Expl., Sheet no. 17 (Springbok Flats), 104 pp. *S. Afr.:* 5; akerite, felsite, trachyandesite.

Wagner, Percy A. (1927b) A new gold discovery in the Rustenburg district, Transvaal: Geol. Soc. S. Afr. Tr. **29,** 95–108. *S. Afr.:* 1 gabbro.

Wagner, Percy A. (1928a) The evidence of the kimberlite pipes on the constitution of the outer part of the earth: S. Afr. J. Sci. **25,** 127–148. *S. Afr.:* 2 eclogite.

Wagner, Percy A. (1928b) The iron deposits of the Union of South Africa: S. Afr. Geol. Surv. Mem. **26,** 264 pp. *S. Afr.:* 3; anorthosite, norite.

Walker, Frederick and Arie Poldervaart (1941) The petrology of the dolerite sill of Downes Mountain, Calvinia: Geol. Soc. S. Afr. Tr. **43,** 159–173. *S. Afr.:* 1 dolerite.

Walker, Frederick and Arie Poldervaart (1942) The metasomatism of Karroo sediments by dolerite: Roy. Soc. S. Afr. Tr. **29,** pt. 4, 285–307. *S. Afr.:* 11; granophyre, dolerite, basalt.

Walker, Frederick (1943a) The origin of the Kentani "gap-dykes" of the Transkei, Cape Province: Roy. Soc. S. Afr. Tr. **30,** pt. 1, 79–83. *S. Afr.:* 1 diorite.

Walker, Frederick and Arie Poldervaart (1943b) The petrology of the Karroo dolerites between Sutherland and Middelburg, C. P.: Geol. Soc. S. Afr. Tr. **45,** 55–64. *S. Afr.:* 4; dolerite, picrite.

WALKER, FREDERICK and GEORGE STEWART (1944) The relationship between the microscopic structure, field characters, and physical properties of Cape road stones: Roy. Soc. S. Afr. Tr. **30,** pt. 3, 183–199. *S. Afr.:* 2; quartzite, slate.

WALKER, FREDERICK (1949) The paragenesis of a hornblende lamprophyre from Bellville, near Cape Town: Roy. Soc. S. Afr. Tr. **32,** pt. 2, 189–194. *S. Afr.:* 1 lamprophyre.

WALKER, FREDERICK (1950a) A mica lamprophyre from Moorreesburg, Cape Province: Roy. Soc. S. Afr. Tr. **32,** pt. 3, 295–299. *S. Afr.:* 1 lamprophyre.

WALKER, FREDERICK (1950b) The occurrence of pumice on the beaches of the Cape Province: Geol. Soc. S. Afr. Tr. **52,** 199–202. *S. Afr.:* 1 pumice.

WALKER, FREDERICK (1951) A volcanic vent near Lambert's Bay (Cape Province): Geol. Soc. S. Afr. Tr. **54,** 1–7. *S. Afr.:* 1 basalt.

WILLEMSE, J. (1934) The petrography and tectonics of the Pretoria-Johannesburg granite: Geol. Soc. S. Afr. Tr. **36,** 1–27. *S. Afr.:* 2 granite.

WILLEMSE, J. (1938) On the Old granite of the Vredefort region and some of its associated rocks: Geol. Soc. S. Afr. Tr. **40,** 43–119. *S. Afr.:* 24; granodiorite, quartz diorite, felsite, diabase, pyroxenite, amphibolite, pseudotachylyte, schist, various hornfels and metamorphics.

WILLEMSE, J. (1950) Die fosfaat-afsetting op Zoetendalesvley 889, Potgietersrustse distrik: Geol. Soc. S. Afr. Tr. **52,** 385–401. *S. Afr.:* 2 dolerite.

YOUNG, R. B. (1921) The rocks of a portion of Portuguese East Africa: Geol. Soc. S. Afr. Tr. **23,** 98–113. *Mozambique:* 5; pitchstone, nepheline syenite, dike, vogesite, basalt.

GEOGRAPHIC INDEX

Index, arranged by country, to references in which are published chemical analyses of rocks from localities within these countries. The author and year of publication relate to the references in the bibliography. The number after each country name is the total number of analyses for that country. The number of analyses in each reference is given in the bibliography.

ALGERIA 154
- GLANGEAUD 1932, 1935, 1939
- LELUBRE 1952
- RANOUX 1952
- ROUBAULT 1934, 1937
- ROYER 1933
- THIÉBAUT 1951

ANGOLA 4
- POLINARD 1939b

BASUTOLAND 2
- STOCKLEY 1947

BECHUANALAND 1
- ROGERS 1935

BELGIAN CONGO 166
- BEUGNIES 1953
- CAHEN 1948
- GROSEMANS 1935, 1951
- GYSIN 1937
- HOLMES 1937b
- JAMOTTE 1934
- MEYER 1953
- MICHOT 1938
- POLINARD 1934, 1935a, 1939a, 1941, 1944a, 1944b
- SOROTCHINSKY 1952
- TAZIEFF 1951
- VERHOOGEN 1940, 1948

CANADA 1
- HOLMES 1937b

EGYPT 40
- BALL 1912
- BARTHOUX 1922
- MEUNIER 1913
- SHUKRI 1945

ENGLAND 2
- BOSAZZA 1937b
- HOLMES 1937b

FRENCH EQUATORIAL AFRICA 49
- BABET 1948
- POLINARD 1935b

FRENCH TOGO 11
- KOURIATCHY 1933

FRENCH WEST AFRICA 157
- Bodin 1951
- Bolgarsky 1950, 1951
- Combier 1935, 1952
- Glangeaud 1941
- Gorodiski 1952
- Jérémine 1939, 1942
- Lacroix 1925, 1926
- Legoux 1939
- Obermuller 1941
- Serpokrylow 1934
- Smith 1952

GOLD COAST 62
- Cooper 1934, 1936
- Hirst 1938, 1942
- Junner 1928, 1929, 1932a, 1932b, 1933, 1936, 1937, 1940, 1943, 1947

INDIA 1
- Holmes 1937b

KENYA 26
- Hitchen 1937
- Pulfrey 1946a, 1946b
- Saggerson 1952

MADAGASCAR 63
- Emberger 1953
- Lacroix 1941
- Roche, de la 1953

MOROCCO 79
- Frey 1936, 1937
- Gigout 1951
- Jérémine 1948, 1950
- Termier 1936, 1950

MOZAMBIQUE 9
- Dixey 1937
- Young 1921

NIGERIA 19
- De Swardt 1953
- King 1949a
- Raeburn 1927

NYASALAND 10
- Alexander 1938
- Cooper 1947
- Dixey 1937

SIERRA LEONE 3
- Junner 1930
- Pollett 1932

SOUTH WEST AFRICA 16
- De Kock 1934
- Gevers 1933, 1934
- Versfeld 1915
- Visser 1948

SOUTHERN RHODESIA 196
- Amm 1940
- Ferguson 1934, 1937
- Golding 1932, 1936
- Keep 1929, 1930
- Lightfoot 1927, 1931, 1939, 1941
- Macgregor 1927, 1928, 1930, 1932, 1935, 1937
- Maufe 1928
- Morgan 1929
- Phaup 1932, 1933, 1937, 1938
- Stagman 1953
- Swift 1953
- Tyndale-Biscoe 1931, 1932, 1933, 1939, 1940, 1949

SPANISH SAHARA 2
- Jérémine 1939

SWAZILAND 2
- Hamilton 1939

TANGANYIKA 24
- Bridges 1936
- Grantham 1945
- Oates 1934
- Stockley 1938, 1948
- Teale 1932
- Temperley 1938
- Wade 1938

TOGOLAND (BRITISH) 1
- Junner 1940

UGANDA 54
- Brammall 1934
- Davies 1942
- Holmes 1937a, 1937b
- King 1939, 1949b
- Roberts 1947
- Simmons 1932, 1935

UNION OF SOUTH AFRICA 640
- Bosazza 1937a, 1937b
- Bouman 1950
- Brink 1950
- Coetzee 1940, 1942a, 1942b
- De Bruyn 1944
- De Swardt 1944
- Ellis 1948

UNION OF SOUTH AFRICA 640—*Contd.*
Fockema 1950, 1952
Fox 1940
Frankel 1937, 1939, 1943a, 1943b, 1944, 1950a, 1950b, 1952
Gevers 1943, 1946
Hall 1912, 1920, 1923, 1924, 1932
Haughton 1924, 1939
Holmes 1937a
Janisch 1927
Jansen 1953
Kent 1949
Latsky 1943
Lombaard 1930, 1931, 1933, 1934, 1935, 1940, 1952
Mathias 1940, 1941
McLachlan 1950
Mountain 1935, 1944, 1945
Nel, H. J. 1941
Nel, L. T. 1935
Nell 1944
Poldervaart 1944, 1948, 1950
Potgieter 1950
Rogers 1917, 1922, 1926
Scholtz 1937, 1947
Shand 1922a, 1922b, 1923, 1929, 1932
Söhnge 1945, 1949
Strauss 1945, 1948a, 1948b, 1951a, 1951b
Taljaard 1937
Torrance 1923, 1924
Van Biljon 1940, 1950
Van der Merwe 1946
Van Eeden 1939
Van Rooyen 1951
Van Zijl, P. J. 1950
Van Zyl, J. S. 1950
Von Backström 1952
Wagner 1921, 1922, 1923a, 1923b, 1924, 1925, 1926, 1927a, 1927b, 1928a, 1928b
Walker 1941, 1942, 1943a, 1943b, 1944, 1949, 1950a, 1950b, 1951
Willemse 1934, 1938, 1950

UNITED STATES 2
Bosazza 1937b
Holmes 1937b

Rock Name Index

Absarokite
leucitic — Holmes 1937b
shoshonitic — Holmes 1937b
Acid rock — Willemse 1938
Adamellite — Golding 1936; Lightfoot 1931; Phaup 1937; Poldervaart 1950; Pulfrey 1946; Tyndale-Biscoe 1939; Wade 1938
porphyritic — Golding 1936
Akerite
hornblende — Wagner 1927a
nepheline — Jérémine 1950
Alaskite — Michot 1938
Albitite — Sorotchinsky 1952; Strauss 1951b
Amphibolite — Babet 1948; Barthoux 1922; Bodin 1951; Bolgarsky 1950; Coetzee 1942a; De Swardt 1953; Junner 1947; Kouriatchy 1933; Lacroix 1941; Michot 1938; Obermuller 1941; Phaup 1932; Polinard 1935a, 1935b, 1939a, 1944a; Roubault 1934; Söhnge 1945; Thiébaut 1951; Willemse 1938
ortho- — Glangeaud 1939; Poldervaart 1950
pyroxene — Polinard 1944a
Analcitite — Gevers 1934
Andesite — Amm 1940; Glangeaud 1939; King 1949b; Macgregor 1937; Swift 1953; Von Backström 1952
hornblende — Hall 1932
soda, carbonated — Golding 1936
Andesite-hyperite (contact rock) — Von Backström 1952

Ankaratrite	Combier 1935; Termier 1936
Anorthosite	Barthoux 1922; Hall 1932; Latsky 1943; Stockley 1948; Van Biljon 1950; Van Zyl, J. S. 1950; Wagner 1924, 1928b
quartz	Beugnies 1953
Aplite	Junner 1947; Lacroix 1941; Morgan 1929; Polinard 1935b; Roubault 1934; Wagner 1921
Appinite, biotite	Holmes 1937a
Banakite	Holmes 1937b
Basalt	Barthoux 1922; Beugnies 1953; Combier 1935; Frey 1936; Golding 1936; Junner 1940; Lightfoot 1939; Lombaard 1952; Phaup 1932; Poldervaart 1948; Stockley 1947; Termier 1936; Van Zyl, J. S. 1950; Walker 1942; Young 1921
epidotized	Golding 1936
melilite	Taljaard 1937
meta-	Bodin 1951; Junner 1928
nepheline	Lombaard 1952; Rogers 1926; Swift 1953
olivine	Haughton 1924; Lightfoot 1939; Swift 1953; Van der Merwe 1946; Walker 1951
porphyritic	Fockema 1950
soda	Strauss 1951a
Basanite	Combier 1952; Frey 1937; Gorodiski 1952; Meyer 1953
leucite	Holmes 1937b
Basanitoid	Combier 1935
Biotite-magnetite-apatite ore	Latsky 1943
Bostonite	Van Biljon 1940
Breccia, felspathic	Dixey 1937
Bronzitite	Hall 1932; Wagner 1924
Calc-chlorite-sericite rock	Junner 1943
Camptonite	Van Biljon 1940
Carbonatite	Fockema 1952; King 1949b; Saggerson 1952; Strauss 1951a, 1951b
Charnockite	Gevers 1943
Chrome-diopside rock	Holmes 1937a
Chromitite	Wagner 1923a
Comendite	Jérémine 1939
Corundum rock	Lacroix 1941; Stagman 1953
Cromaltite	Jérémine 1950
Dacite	Barthoux 1922; Frey 1936
meta-	Glangeaud 1939
Dacitoid	Glangeaud 1932, 1935, 1939; Jérémine 1939; Termier 1936
Dellenite	Glangeaud 1932, 1939; Roubault 1937
Dellenitoid	Glangeaud 1939
Diabase	Barthoux 1922; De Kock 1934; Fox 1940; Frankel 1937; Lombaard 1930, 1935; 1940; Michot 1938; Nel, H. J. 1941; Willemse 1938
enstatite	Hansen 1953
metamorphosed	Frankel 1952
Diallagite	Thiébaut 1951
Dike	Cooper 1934; Hirst 1938; Junner 1932a, 1933, 1937; Poldervaart 1950; Van Biljon 1940; Van Zijl, P. J. 1950; Young 1921
Diopside rock	Van Biljon 1950
Diopside-biotite-magnetite ore	Latsky 1943

Diorite	Barthoux 1922; Bodin 1951; Bolgarsky 1950; De Kock 1934; Glangeaud 1939; Grosemans 1951; Jérémine 1942; Junner 1928; Tyndale-Biscoe 1933; Versfeld 1915; Van Zyl, J. S. 1950; Walker 1943a
augite	Van Biljon 1950
fayalite	Strauss 1951a
hornblende	Latsky 1943
mica	Latsky 1943; Rogers 1917
micro-	Barthoux 1922; Bodin 1951; Frey 1936; Kouriatchy 1933
quartz	Babet 1948; Bodin 1951; Bolgarsky 1950; Frey 1937; Junner 1936; Kouriatchy 1933; Lombaard 1940; Van Zijl, P. J. 1950; Willemse 1938
quartz-hypersthene	Gevers 1943
Dissogénite	Lacroix 1941
Dolerite	Babet 1948; Bouman 1950; Cahen 1948; De Swardt 1944; Fockema 1950; Frankel 1939, 1943, 1944, 1950b; Grosemans 1951; Jérémine 1939, 1942; Junner 1928, 1936; Lombaard 1940, 1952; Michot 1938; Mountain 1944; Nell 1944; Phaup 1937; Polinard 1939a, 1941, 1944a; Potgieter 1950; Strauss 1948a, 1951a; Swift 1953; Termier 1936; Torrance 1923; Walker 1941, 1942; Willemse 1950
albite	Junner 1947
chloritized	Polinard 1941
fayalite-quartz	Poldervaart 1944
hypersthene	Walker 1943b
iron-rich	Junner 1940
meta-	Glangeaud 1939
micro-	Grosemans 1951
nepheline	Swift 1953
oligoclase	Junner 1940
olivine	Ferguson 1934; Golding 1936; Lombaard 1940; Maufe 1928; Poldervaart 1944, 1948; Walker 1942, 1943b
para-	Glangeaud 1939
quartz	Golding 1936; Poldervaart 1944; Polinard 1944a; Strauss 1948a
quartz, carbonated	Golding 1936; Keep 1929
Dolerite pegmatite	Walker 1942
Dunite	De Bruyn 1944; Junner 1930; Keep 1929; Lacroix 1941; Wagner 1925
Eclogite	Holmes 1937a; Kouriatchy 1933; Swift 1953; Wagner 1928a
Embrèchite	Thiébaut 1951
Enstatite rock	Lightfoot 1941
Epidiorite	Amm 1940; Ferguson 1934; Frankel 1943; Golding 1936; Junner 1929; Thiébaut 1951; Tyndale-Biscoe 1931, 1933
carbonated	Golding 1936
Epidosite	Golding 1936
Epidote rock	Lacroix 1941
Epidotite	Grosemans 1951
Fasinite	Jérémine 1948; Termier 1936
Felsite	Hitchen 1937; Lightfoot 1931; Lombaard 1933, 1935; Van Biljon 1940; Wagner 1927a
andesitic	Lombaard 1931
quartz	Scholtz 1947; Willemse 1938
Foyaite	Dixey 1937; Lombaard 1940; Shand 1922a, 1923, 1929; Strauss 1951a
micro-	Shand 1929

Foyaite aplite	Van Biljon 1950
Fuchsite rock	Ferguson 1937
Gabbro	Babet 1948; Beugnies 1953; Bolgarsky 1950; Brink 1950; Fockema 1952; Jamotte 1934; Latsky 1943; Nel, H. J. 1941; Polinard 1935a, 1944a; Roubault 1934; Van Biljon 1950; Van Zijl, P. J. 1950
enstatite	Jansen 1953
hornblende	Michot 1938
hypersthene	Babet 1948; Jérémine 1939; Legoux 1939
leuco-	Stockley 1948
meta-	King 1949a; Poldervaart 1950
meta-, granitized	King 1949a
micro-	Jérémine 1942; Kouriatchy 1933
olivine	Golding 1936; Junner 1928; Lightfoot 1939; Shukri 1945; Stockley 1948
quartz	Beugnies 1953; Lombaard 1933; Polinard 1944a
scapolite-quartz	Bridges 1936
soda	Wagner 1927b
theralitic	Grosemans 1935
uralitic	Junner 1932a
Gabbro-diorite	Polinard 1944a; Van Zijl, P. J. 1950
Gabbro pegmatite	Scholtz 1937
anorthositic	Shukri 1945
Ganister	Bosazza 1937b
Garnet rock	Alexander 1938; Lacroix 1941; Raeburn 1927
Garnet-diopside-wollastonite rock	Willemse 1938
Garnet-grunerite rock	Willemse 1938
Garnet-quartz-feldspar rock	Willemse 1938
Gauteite	Fockema 1950
Glass	Kent 1949; Smith 1952
volcanic	Junner 1933
Glassy rock	Frankel 1950a
Gneiss	Babet 1948; Bolgarsky 1950; De Swardt 1953; Jérémine 1942; King 1949a; Lelubre 1952; Michot 1938; Obermuller 1941; Poldervaart 1950; Polinard 1934, 1935a, 1935b, 1944a; Roubault 1934; Swift 1953; Thiébaut 1951
augen	Royer 1933
biotite	Poldervaart 1950; Polinard 1935a; Roubault 1934
chlorite	Polinard 1944a
dioritic	Babet 1948
garnet	Roubault 1934
hornblende	Söhnge 1945
hypersthene-biotite	Babet 1948
monzonitic	Babet 1948
porphyritic	Tyndale-Biscoe 1940
Granite	Amm 1940; Barthoux 1922; Beugnies 1953; Bodin 1951; Bolgarsky 1950; Brammall 1934; Brink 1950; Coetzee 1942b; De Kock 1934; De Swardt 1953; Fockema 1952; Frey 1936; Gigout 1951; Glangeaud 1932, 1939; Grantham 1945; Gysin 1937; Hall 1932; Hamilton 1939; Jérémine 1942; Keep 1929; 1930; King 1939, 1949a; Lacroix 1926; Legoux 1939; Lelubre 1952; Lombaard 1933, 1935; Macgregor 1930, 1932, 1937; Mathias 1941; Michot 1938; Obermuller 1941; Polinard

Granite—*contd.*	1935a, 1935b, 1939a, 1939b, 1944a; Pollett 1932; Potgieter 1950; Roche, de la 1953; Roubault 1934, 1937; Saggerson 1952; Scholtz 1947; Shand 1932; Söhnge 1945, 1949; Stagman 1953; Stockley 1938; Strauss 1945, 1951a; Termier 1950; Thiébaut 1951; Torrance 1923; Tyndale-Biscoe 1933, 1949; Van Biljon 1940; Wagner 1921, 1922, 1924; Willemse 1934
aplo-	Coetzee 1942b; King 1949a; Tyndale-Biscoe 1940
akeritic	Jérémine 1939
biotite	Coetzee 1942b; Hirst 1942; Jérémine 1939; Junner 1928, 1936, 1947; Polinard 1935a; Potgieter 1950; Wade 1938
biotite-muscovite	Junner 1928
gneissic	Macgregor 1930; Tyndale-Biscoe 1939, 1940
granophyric	Scholtz 1947
hornblende-biotite	Junner 1947
hypersthene	Bolgarsky 1950; Legoux 1939
micro-	Barthoux 1922; Bodin 1951; Gigout 1951; Glangeaud 1939; Jérémine 1939; Lacroix 1926; Lelubre 1952; Lombaard 1952; Ranoux 1952; Roubault 1934; Scholtz 1937
micro-, hybrid	Scholtz 1947
monzonitic	Kouriatchy 1933; Lacroix 1926
porphyritic	Phaup 1933; Scholtz 1947
soda	Golding 1936; Junner 1928
tourmaline	McLachlan 1950; Scholtz 1947
Granite aplite	Van Biljon 1940
Granite gneiss	De Swardt 1953; Gysin 1937; King 1949a; Mathias 1941
Granite syenite	Michot 1938
Granitoid rock	Polinard 1935b
Granodiorite	Bodin 1951; Coetzee 1942b; Glangeaud 1932, 1939; Golding 1936; Jérémine 1939; Junner 1940; Kouriatchy 1933; Lacroix 1926; Lightfoot 1931; Lombaard 1940; Phaup 1938; Polinard 1939a, 1944a; Roubault 1934; Scholtz 1947; Willemse 1938
gneissic	Golding 1936; Junner 1936
micro-	Bodin 1951; Jérémine 1942; Roubault 1934
micro-, quartz	Glangeaud 1932
porphyritic	Golding 1936
pyroxene	Temperley 1938
Granodiorite-granite	Polinard 1944a
Granophyre	Ellis 1948; Lightfoot 1939; Lombaard 1933, 1935, 1952; Poldervaart 1944; Saggerson 1952; Strauss 1948a, 1951a; Swift 1953; Van Biljon 1950; Wagner 1921; Walker 1942
pseudo-	Van Rooyen 1951
Granulite	Bridges 1936; Gigout 1951; Holmes 1937a; Poldervaart 1950; Roubault 1934; Simmons 1935; Stagman 1953; Swift 1953; Van Biljon 1950
andalusite	Ferguson 1937
hypersthene	Gevers 1943
pyroxene	Golding 1936
Greenstone	Golding 1936; Phaup 1937, 1938
actinolitic	Macgregor 1937
augitic	Keep 1929
limburgitic	Macgregor 1928
Grunerite rock	Willemse 1938
Harzburgite	Holmes 1937a; Lightfoot 1927; Wagner 1924

Hornblendite	Michot 1938; Van Zyl, J. S. 1950
Hornfels	Michot 1938; Roubault 1934; Torrance 1924; Tyndale-Biscoe 1949; Van Biljon 1950
biotite-hypersthene-cordierite	Willemse 1938
cordierite	Willemse 1938
sillimanite-cordierite	Willemse 1938
Hornstone	Junner 1947
Hyperite	Von Backström 1952
olivine	Scholtz 1937
quartz	Scholtz 1937
saussurite	Von Backström 1952
Hypersthene-garnet-magnetite rock	Söhnge 1945
Hypersthenite	Latsky 1943; Legoux 1939
Idocrasite	Lacroix 1941
Ijolite	Saggerson 1952; Shand 1922a; Strauss 1951a; Swift 1953
Katungite	Holmes 1937b
biotite	Holmes 1937a
Kentallenite	Roubault 1934
Keratophyre	Junner 1928; Macgregor 1932
quartz	Rogers 1922
Kersantite	Jérémine 1950; Van Biljon 1940
Kimberlite	Verhoogen 1940
Kivite	Holmes 1937b; Tazieff 1951
Labradoritite	Barthoux 1922; Glangeaud 1939
Lamboanite	Lacroix 1941
Lamprodiorite	Van Zijl, P. J. 1950
Lamprophyre	
hornblende	Walker 1949
mica	Walker 1950a
Latite, hypersthene	Holmes 1937b
Lava	Junner 1937; Nel, L. T. 1935; Rogers 1922, 1926; Verhoogen 1948
acid	Fockema 1950
pillow	Macgregor 1935
pillow, basaltic	Macgregor 1937
pillow, metamorphosed	Golding 1936
Lepidolite rock	Tyndale-Biscoe 1932
Leptite	Strauss 1948b; Van Rooyen 1951
Lestiwarite	Strauss 1951a
Leucitite	Holmes 1937b
olivine	Holmes 1937b
Lherzolite	Holmes 1937a; Obermuller 1941; Roubault 1934
Limburgite	Ferguson 1934; Lombaard 1952; Tyndale-Biscoe 1949
Magnesite rock	Morgan 1929
Magnetite-barite rock	Mathias 1940
Magnetite-hypersthene-garnet rock	Willemse 1938
Marble	Fockema 1952; Junner 1947; Serpokrylow 1934
magnesite	Macgregor 1932
Marundite	Hall 1923
Melanephelinite	King 1949b
olivine	King 1949b
Melilitite, olivine	Holmes 1937a

Metamorphosed limestone	Serpokrylow 1934; Thiébaut 1951
Metamorphosed grit	Poldervaart 1944
Metamorphosed rock	Roubault 1934
Metamorphosed sediments	Mountain 1945
Meteorite	Ball 1912; Gevers 1946; Golding 1936; Haughton 1939; Lacroix 1925; Meunier 1913; Mountain 1935; Roberts 1947
Migmatite	Polinard 1935b
Mikenite	Holmes 1937b
Miscellaneous	
"Chert"	Van Biljon 1950
Footwall country rock	Golding 1932
Fragment from agglomerate	Dixey 1937
Intermediate rock	Lombaard 1933; Van Biljon 1950
Platinum reef rock	Golding 1932; Lightfoot 1927
Monchiquite	Jérémine 1950
Monzonite	Bodin 1951; Glangeaud 1939; Jérémine 1950; Lacroix 1926; Roubault 1934; Tyndale-Biscoe 1939
hypersthene	Tyndale-Biscoe 1939
olivine	Tyndale-Biscoe 1939
quartz	Glangeaud 1932
quartz-hypersthene	Scholtz 1937
Monzonite granite	Roubault 1937
Monzonite microgranite	Glangeaud 1932
Mugearite	Barthoux 1922
Murambite	Holmes 1937b
Murite	Termier 1936
Nephelinite	King 1949b; Saggerson 1952; Swift 1953
melilite	King 1949b
olivine	King 1949b
Norite	Babet 1948; Bolgarsky 1950; Golding 1936; Hall 1924; King 1949a; Latsky 1943; Legoux 1939; Lightfoot 1927; Lombaard 1933, 1935; Poldervaart 1950; Rogers 1917, 1922; Stockley 1948; Van Biljon 1950; Wagner 1925, 1926, 1928b
anorthositic	Junner 1932a; Wagner 1924
biotite-quartz	Polinard 1944a
diallage	Wagner 1924
enstatite	Jansen 1953
hornblende	Wagner 1926
hybrid	Hall 1924
magnetite	Lombaard 1933
olivine	Junner 1932a
olivine, pyroxenitic	Wagner 1924
quartz	Kouriatchy 1933; Polinard 1944a, 1944b; Rogers 1922; Van Biljon 1950
Norite diabase	Lombaard 1935
Obsidian	Frey 1936
Oligoclasolite, quartz	Roche, de la 1953
Orthoclase rock	Dixey 1937
Pegmatite	Golding 1936; Lacroix 1941; Phaup 1938; Polinard 1935b, 1944a; Simmons 1935
micro-	Barthoux 1922
garnet	Thiébaut 1951

Pegmatite, schist, and apatite rock	Janisch 1927
Pegmatitoid	Combier 1952
Peridotite	Junner 1928, 1930; Oates 1934
amphibole	Bridges 1936; De Bruyn 1944
augite-biotite	Holmes 1937b
Perknite	Swift 1953
Phlogopite-glimmerite	Holmes 1937a
Phlogopitite	Lacroix 1941
Phonolite	Dixey 1937; King 1949b; Polinard 1939b; Saggerson 1952; Shand 1923; Termier 1936
Phyllite	Cooper 1936; Ellis 1948; Junner 1943, 1947; Scholtz 1947
chloritoid	Junner 1932a
porphyritic	Grosemans 1951
Picrite	Poldervaart 1944; Strauss 1951b; Walker 1943b
bronzite	Scholtz 1937
hypersthene	Scholtz 1937
Pitchstone	Young 1921
Plagioclasite	Lacroix 1941; Legoux 1939
Plauenite	Bodin 1951; Jérémine 1942, 1950
Pleonaste rock	Strauss 1951b
Plumasite	Hall 1923
Porphyrite	Tyndale-Biscoe 1931
Porphyry	Golding 1936; Macgregor 1930; Rogers 1935; Wagner 1923b
aegirine	Macgregor 1930
albite	Junner 1936
andesite	Golding 1936
diallage	Jansen 1953
feldspar	Visser 1948
foyaite	Shand 1923
granite	Scholtz 1947; Van Biljon 1940
granite, sodic	Junner 1932a
monzonite, olivine	Tyndale-Biscoe 1939
nepheline syenite	Young 1921
quartz	De Kock 1934; Lightfoot 1931; Phaup 1937, 1938; Scholtz 1947; Tyndale-Biscoe 1933; Von Backström 1952
Prehnite-aegirine rock	Strauss 1951b
Pseudotachylyte	Willemse 1938
Pumice	Walker 1950b
Pyroxenite	Babet 1948; Bolgarsky 1950; Hall 1920; Jérémine 1942, 1950; Junner 1928; Lacroix 1941; Latsky 1943; Lightfoot 1941; Lombaard 1935; Obermuller 1941; Rogers 1922; Van Biljon 1950; Willemse 1938
amphibole	Legoux 1939
biotite	Holmes 1937b
biotite-hornblende	Holmes 1937b
enstatite	Lightfoot 1941; Van Biljon 1950
olivine-biotite	Holmes 1937b
Quartz carbonate rock	Golding 1936
Quartzite	Bolgarsky 1951; Bosazza 1937a, 1937b; Ellis 1948; Hall 1912; Legoux 1939; Mountain 1944; Obermuller 1941; Polinard 1935b; Scholtz 1947; Strauss 1948b; Van Biljon 1940; Walker 1944
Rhyolite	Barthoux 1922; Ferguson 1934; Frey 1936; Glangeaud 1932, 1939; Jérémine 1942; Lelubre 1952; Lightfoot 1939; Lombaard 1952; Roubault 1934; Tyndale-Biscoe 1933, 1940; Von Backström 1952

Sagvandite	Lacroix 1941
Sakenite	Lacroix 1941
Saxonite	Holmes 1937a
Scapolite rock	Lacroix 1941
Schist	Bodin 1951; Bolgarsky 1950; Gysin 1937; Hall 1912; Polinard 1935b; Roubault 1934; Royer 1933; Termier 1950; Thiébaut 1951
actinolite	Willemse 1938
andalusite	Potgieter 1950
biotite	Tyndale-Biscoe 1933; Van Eeden 1939
calc-chlorite	Junner 1932a, 1947
chlorite	Ferguson 1934
greenstone	Ferguson 1934; Phaup 1938
hornblende	Ferguson 1934; Golding 1936; Phaup 1932; Söhnge 1945
kyanite	Cooper 1947; Emberger 1953
quartz-sericite	Poldervaart 1950
sericite	Royer 1933
talc	Davies 1942
talc-carbonate	Morgan 1929; Tyndale-Biscoe 1949
talc-magnesite	Macgregor 1932
tremolite	Junner 1932b
Schist-granite (transition rock)	Thiébaut 1951
Serpentine	Ferguson 1934; Golding 1936; Keep 1929, 1930; Kouriatchy 1933; Lightfoot 1927; Macgregor 1930, 1937; Morgan 1929; Phaup 1932, 1937; Stockley 1948; Tyndale-Biscoe 1949; Wagner 1924
silicified	Golding 1936
Serpentine-spinellid rock	Golding 1936
Silcrete	Bosazza 1937b
Sillimanite-corundum rock	Coetzee 1940
Slate	Walker 1944
Soapstone	Pulfrey 1946
Sölvsbergite	Barthoux 1922; Dixey 1937; Rogers 1922
Spessartite	Van Biljon 1940
Spilite	Macgregor 1927
Syenite	Fockema 1950; Hall 1932; Lacroix 1926; Lombaard 1940; Macgregor 1930; Shand 1922b, 1929, 1932; Strauss 1951a; Teale 1932; Van Biljon 1940
albite-augite	Lombaard 1933
aplo-	Wade 1938
meta-	Versfeld 1915
micro-	Barthoux 1922; Gevers 1933; Saggerson 1952
nepheline	Barthoux 1922; Jérémine 1950; Junner 1928; Polinard 1939b
quartz	Fockema 1952; Strauss 1951a
sodalite	Jérémine 1950
Syenogranite	Stockley 1948
Tahitite	Termier 1936
Talc-carbonate rock	Keep 1929
Talc-serpentine-carbonate rock	Keep 1929
Theralite	Combier 1952; Strauss 1951a
magnetite	Strauss 1951a
Tholeiite	Poldervaart 1944, 1948
pigeonite	Poldervaart 1948

Tinguaite	Barthoux 1922
Tonalite	Beugnies 1953; Golding 1936; Phaup 1932; Strauss 1948a; Tyndale-Biscoe 1931
biotite-hornblende	Simmons 1932
gneissic	Golding 1936
soda	Phaup 1932
Trachyandesite	Frey 1937
soda	Wagner 1927a
Trachybasalt	Junner 1940
Trachyte	Barthoux 1922; Fockema 1950; King 1949b; Lelubre 1952; Lombaard 1934; Polinard 1939b
porphyritic	Dixey 1937
soda	Shand 1922b
Trachytoid rock	Barthoux 1922
Troctolite	Scholtz 1937
Tuff	Junner 1937; Macgregor 1930
andesitic	Saggerson 1952
basaltic	Junner 1928
Ugandite	Holmes 1937b
Umptekite	Strauss 1951a
Vogesite	Young 1921
Websterite	Barthoux 1922; Keep 1930; Lightfoot 1927
Wehrlite	De Bruyn 1944
Xenolith	Scholtz 1947
core	Poldervaart 1944
granitized	McLachlan 1950
granitized, hybrid	Scholtz 1947

LETTER TO THE EDITORS

Trace-metal anomalies in sedimentary rock over petroleum-bearing horizons*

(*Received* 17 *January* 1956)

In connection with the basic geochemical studies in Israel, we examined samples of two drill-cores, obtained in the exploration for oil, for their trace-metal content. Both drill-cores represent the same kind of rock limestone and sediments—having the same kind of structure, as established geophysically, and being situated in one and the same geochemical province. One of these cores, here designated as "1," yielded no oil whatsoever, notwithstanding the otherwise favourable prospecting indications. The second one, "2," yielded some apparently economic oil, in more than one horizon.

The "2" ("over oil") core contained anomalous quantities of nickel in the sediment as well as in the overlying limestone, and anomalous quantities of copper, zinc, and gold. The "1" core contained not more than a few tens of p.p.m. of nickel and copper, some zinc, and a trace of extractable gold, in all of the fourteen horizons examined. The metals here named were determined polarographically, except gold, which was isolated physically, by procedures developed in our laboratory.

A fuller report on these findings is now in preparation.

We are indebted to Isramco and Lapidoth Companies for the use of their materials.

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Book reviews

S. I. Tomkeieff: **A New Periodic Table of the Elements** (based on the structure of the atom). Chapman and Hall, London. 30 pages. 10s net.

The search for regular variations of elemental properties has fascinated chemists for some time, and, beginning in the early nineteenth century, led eventually to the well-known periodic arrangement and tables of Lothar Meyer and Mendeleev, respectively. This quest did not stop there, however, and a whole array of tables have since appeared, each attempting to reveal in the most convenient and useful way variations and groupings of properties of the elements. The table under review is a new example. As in previous examples, the elements are arranged in order of their atomic number. A table of elements is first presented, giving such data as abundance, electronic structure, colour of element, normal state (gas, metal, non-metal) of element, year of discovery, and name derivation; finally, spiral-shaped and conical-shaped periodic charts are presented and discussed. Some spirals have been contoured so as to indicate distribution of such properties as specific gravity of element and its abundance in meteorites. (The abundance data are from a 1935 publication of Goldschmidt, and would benefit from revision.) Although, perhaps, from fundamental considerations little new is revealed by re-arranging the same property (atomic number, weight, etc.; and not, say, screening or some other fundamental property) in a different way, the tables and charts will be of interest to the student of the periodic table itself, and of use to those requiring a ready reference to such properties as abundance, colour, etc., of elements.

L. H. Ahrens

Yasuo Miyake, **Chikyu-Kagaku (Geochemistry)**. Asakura-Shoten Co., Tokyo, 1954, 386 pp. 780 yen.

"It is my belief that geochemistry should be brought closer to geophysics to be of better service to the other branches of the entire earth-sciences," says the author of this remarkable book on geochemistry, written in the Japanese language. It will be certainly quite a shock to the majority of geochemists to find that well over three-quarters of the total pages in this book are devoted to the fields other than the lithosphere. The book is divided into six chapters as follows: Chapter I, Cosmochemistry (71 pages), Chapter II, Atmosphere (88 pages), Chapter III, Hydrosphere (82 pages), Chapter IV, Earth Crust (73 pages), Chapter V, Interior of the Earth (22 pages), Chapter VI, Age Determinations (24 pages). Chapters II and III are probably the best-written part of this valuable book, reflecting the past experience of the author as the head of the Geochemistry Division of the Central Meteorological Observatory of Japan for more than two decades. Dr. Miyake has also made an admirable effort in introducing modern theories of astronomy and cosmochemistry, as well as geophysics, into a book of limited size. The author explains that Chapter IV has been intentionally condensed to avoid duplication and repetition of other geochemistry books. It is regrettable that a chapter on the biosphere is missing. Current views of Latimer, von Weizsäcker, Urey, Brown, and others are fully presented, while the classical theory of Goldschmidt is critically reviewed, and Bowen's theory on the evolution of igneous rocks is totally omitted. Thus, it appears to the reviewer that the geochemical importance of the fundamental principles of crystal chemistry and phase rule is not at all emphasized in this book. The author proposes to express the chemical composition of igneous rocks in terms of atomic percentages, and shows that the following simple relations exist between the atomic percentages of oxygen [O], silicon [Si], and metals including H [R]; [O] = 1/2 + 1/2[Si], [O] = 2/3–1/3 [R], and [Si] = 1/3–2/3 [R]. Chapter V is short, but nicely

arranged. It is felt, however, that some of the pioneer works by Japanese seismologists should have been included in this chapter; as an example, the first direct measurements of the velocities of seismic waves in the core by WADATI and MASUDA (1933). It is certainly refreshing to find numerous mathematical equations throughout this book, although the derivations are generally omitted, and ambiguous statements here and there often jeopardize the entire effort of the reviewer to follow them. The book gives an excellent collection of references on western work in certain chapters, but Japanese references are not fully covered.

P. K. KURODA.

NEWS AND NOTES

Fifth National Clay Conference

THE Fifth National Clay Conference will be held at the University of Illinois, Urbana, Ill., 8, 9, and 10 October 1956. The conference is sponsored annually by the Clay Minerals Committee of the National Academy of Sciences—National Research Council, under the chairmanship of Prof. R. E. GRIM of the University of Illinois.

Contributed papers on subjects related to clay mineralogy or technology will be welcome. Titles for inclusion in the programme must be received by 1 May, and short informative abstracts will be required by 15 June. Titles and abstracts may be sent to Dr. W. F. BRADLEY, Illinois Geological Survey, Urbana, Illinois.

More detailed announcements will be distributed about 1 April.

News and Notes

SYMPOSIUM ON GEOCHEMISTRY, JULY 1957

THE Commission on Geochemistry of the International Union of Pure and Applied Chemistry is planning to hold a symposium on geochemistry as part of the meeting of the Section of Inorganic Chemistry, to be held in Paris in July 1957, perhaps 16–22 July. Professor E. RAGUIN, Ecole des Mines, 60 Boulevard Saint-Michel, Paris VI, has kindly agreed to serve as chairman of the committee making the arrangements. It would help the committee greatly if everyone who hopes to attend would notify Professor RAGUIN of, (1) his intention to come, (2) the title of a paper he would like to present, and (3) suggestions as to suitable subjects for symposium sessions.

Plans are at present indefinite, but there may be three days of scientific sessions and a two-day field trip, perhaps to the Auvergne region. Additional information about the symposium will be published in a forthcoming issue of this journal.

KALERVO RANKAMA
Secretary,
Commission on Geochemistry

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It is in those branches of natural science which border older established disciplines that the need for critical survey reviews of progress has become greatest. This has arisen partly because subjects such as geochemistry and geophysics fringe and overlap so many other fields and partly because they are at present vigorous growing points in science. A principal aim of the annual series, Chemistry and Physics of the Earth, will be to provide authoritative and up-to-date surveys of progress for those actively engaged in geophysics and geochemistry. But it is hoped also that much of what is written will encourage the interest of the chemist and physicist in a study of our planet, not merely for its own sake, but because such a study often turns out to be of benefit to physics and chemistry. Another aim is to acquaint the geologist with the results and methods of geophysics and geochemistry, particularly as progress in earth science has been hindered by some lack of liaison between different groups. An attempt will be made to provide a balanced variety of topics with roughly equal emphasis on chemistry and physics, but certain topics will be considered fairly regularly.

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